PROSPECTOR IX:

HUMAN POWERED SYSTEMS TECHNOLOGIES

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PREFACE

The concept for a series of highly focused workshops dealing with key issues associated with the science and technology of advanced power systems had its origin in many conversations with outstanding technologists all over the world. It became apparent that the difference between the state-of-the-art and what these technologists saw for future needs was so large that new approaches to meet these needs was mandatory. There are a host of key issues which fall into this category such as prime power, thermal management, advanced energy conversion, life support, automated systems and advanced diagnostic techniques just to name a few. Due to the interdisciplinary nature of power systems, any new and successful approach will likely come from a group with diverse backgrounds rather than those schooled in the classic approaches.

Power systems offer unique challenges to engineers and application specialists. While a capability or mission may be feasible, more often than not, the power technology available determines the total mission profile. As the mission profile expands, the demands on the power technology associated with the mission quickly extend beyond the state-of-the-art. For many advanced concepts, power technology is totally enabling. It is not just the "long pole in the tent", it is the "tent". For example, a soldier's rucksack weight for an average mission weighs approximately 115-140 lbs. This weight is approximately 50% batteries and charging devices, which can inhibit the soldier's mobility. Therefore, improvements are needed to provide the frontline soldier with lighter-weight power and recharging capability since he has no source of AC power near the frontline for recharging operations. Often promising concepts are abandoned due to the lack of a foreseeable power technology which could remove it from being a laboratory curiosity. It is insufficient to think totally in terms of system energy density or power density. Due to environmental and safety concerns, the power technologist may be forced to employ non-optimum power systems which drastically limit the performance envelope. Further, the use of exotic materials, exotic fuels, and complexity, reliability etc. further impede the transition from laboratory curiosity to field workhorse. Recalling that "energy and mass are neither created nor destroyed but simply changed from one form to another", energy carried within the system, stored in the chemical bond or in the nucleus, must eventually be used as intended or ejected from the system in the form of "low grade heat". Three options exist for managing waste energy. Having changed its thermodynamic state when useful work was done with it, the excess energy can either be radiated away to space, stored, or convected/conducted into a flowing coolant stream. Each of these techniques has its advantages and disadvantages, almost always adding to the system mass. Clearly, there is a set of tradeoff parameters which must be manipulated to provide an optimum system for a given mission and it goes without saying that it is impossible to achieve the optimum in all parameters simultaneously.

At the request of The Army Research Office, a workshop dealing with Human Powered Systems technology was organized and held at the Washington Duke Inn & Golf Club. This workshop, Prospector IX, is the ninth in the series. All have dealt with power technology and are interrelated to this workshop. The following is a list of the Prospector Workshops and individual focus:

- Prospector I, Thermal Management of Space Based Assets,
- Prospector II, Radioisotope Power Systems,
- Prospector III, High Energy Density, High Power Density Power Sources R&D,
- Prospector IV, Small Engines and Their Applicability to the Soldier Systems,
- Prospector V, Microelectromechanical Systems, Their Applicability to the Soldier System,

- Prospector VI, Electric Actuation,
- Prospector VII, Small Fuel Cells for Portable Power,
- Prospector VIII, Thermophotovoltaics, An Update on DoD, Academic, and Commercial Research, and
- Prospector IX, Human Powered Systems Technologies.

In addition to the above Prospector series of workshops, The Army Research Office sponsored a workshop entitled "Mobile Battlefield Power Workshop," which was conducted in the same format as the Prospector series. All of these workshops produced technical documents which clearly identify key issues which must be addressed to advance the art and all have potential Army applications.

The focus of Prospector IX is to assess whether or not Human Powered Systems are capable of meeting some of the electrical energy needs of the Dismounted Soldier in the field. The requirements placed on power technology by the "Soldier System" concept are as demanding as that of any spacecraft and shares many common requirements such as extreme reliability, safety, minimum weight and volume and, of course, the ever increasing demands placed due to environmental concerns.

There is always something in a name. Just as the prospectors of old sometimes worked the tailings of old diggings searching for a missed nugget, we too reviewed the current techniques "looking for nuggets", before embarking on a search of new ground. For this we assembled a wide range of technologists--engineers, physicists, physiologists, manufacturing specialists, and managers representing the government laboratories, industry and the university community. The groups were charged with evaluating Human Powered Systems technologies which might be relevant to the Dismounted Soldier .

In keeping with the tradition of the previous Prospectors, the workshop was patterned after the highly successful Gordon Conferences which have formal morning and evening sessions, leaving the afternoon free for recreation, small group discussions or laboratory tours at the participants' discretion.

The workshop was directed by a group of senior scientists from the Army Research Office, DARPA, CECOM, and The Space Power Institute at Auburn University. The broad technical base represented by the Board of Directors resulted in a unique agenda which covered many of the technologies relevant to Human Powered Systems. The Board members are Dr. Donna Cookmeyer, and Dr. Richard Paur from the Army Research Office, Ms. Mary Hendrickson, from CECOM, Dr. Robert Nowak from DARPA, and Dr. Henry Brandhorst and Dr. Frank Rose from the Auburn University Space Power Institute.

The workshop organizers would like to express thanks to the administrative staff of the Washington Duke Inn & Golf Club, Durham, NC, and to the Administrative Staff of the Space Power Institute for organizing and managing the workshop. Special thanks are due to Ms. Gail Edwards and Ms. Mickie Jacob whose efforts contributed greatly to the success of the workshop and to this archival record.

The pages that follow contain a detailed record of the workshop procedures, an Executive Summary, the results and recommendations of the working groups, copies of the individual technical presentations and a list of the attendees. The attendees were key technologists from government, industry and academia. We appreciate their willingness to give their time and technical skills for this meeting and sincerely hope that this document represents an accurate

distillation of the workshop deliberations. It is, after all, their collective opinion which is archived here and whatever impact this document has in the future is due to their deliberations.

We hope to see many of you at Prospector X.

M. Frank Rose, Director
For the Board of Directors

EXECUTIVE SUMMARY

With the evolutionary advances in commercial communication electronics, power consumption of these devices has been reduced to around the 1 to 5-Watt level using power management techniques and low power electronics. At this power level, the feasibility of harvesting energy from the human body to power man-worn electronics is conceptually possible. It appears possible through the use of sophisticated energy management and through low power electronics to reduce the demand for energy by the Dismounted Soldier to a level where it is instructive to examine the potential for the Soldier to produce enough electrical power to provide a substantial amount of the electrical energy needed for a mission. In order to do this, it will be necessary to convert to electricity some of the energy expended by the Soldier during everyday actions.

The human body stores an enormous amount of energy. The energy available from a donut is equivalent to **347 Whr**. The average persons body is approximately 15% fat and represents a stored energy greater than **11,000 Whr**. The average person consumes between **2000 Kcal** and **3000 Kcal per day**, which is, in more familiar units, approximately **2200 Whr** and **3300 Whr**. Since it can take 30 minutes to consume the food with the above energy content, the "charge rate" is about 7 kW for the higher caloric intake. Clearly the amount of energy consumed by an individual is sufficient to provide energy for electronic devices if a suitable method can be found to convert **a small fraction** of that energy to electricity.

The idea of taking some of the energy normally associated with the activities of the human body and converting it to electricity to power external devices is novel, but not new, and has enormous potential if it can be done with modest efficiency and in an unobtrusive manner. This technology is unique and has significant promise for the development of portable power sources for the Dismounted Soldier. Consequently, a workshop on Human Powered Systems was held at the Washington Duke Inn & Golf Club, on November 2-5, 1997, sponsored by the Army Research Office.

To accomplish the objectives of the workshop, a group of scientists, active in technologies relevant to the field, from government laboratories, industry and academia were invited to lecture on a wide range of topics. The technical program consisted of plenary and state-of-the-art sessions covering as wide a range of relevant topics as the allotted time permitted.

With respect to the military, this field is new and innovative but there have been applications of human power to electrical/mechanical systems for decades. Indeed, the hand-cranked portable generator currently employed by special forces falls into this category. It is possible to generate up to 100 watts in this fashion. Devices of this type are not passive and their use effectively immobilizes the individual while power is being generated. The noise generated when operating this device, often make the use of this mechanism unfeasible due to requirements of covert activities. The weight and size of these hand-cranks makes portability less attractive in frontline mission scenarios. A second example is the small "flashlight" which is energized by squeezing a lever. For purely mechanical conversion, the Apollo astronauts took with them to the moon a rotary shaver which employed a small flywheel energy store activated by pulling a cord. Commercially, there is a wind-up radio available from Baygen, and a night vision/starlight scope, manufactured in Russia and available from the Edge Company. Except for the items cited above, there does not appear to be any concerted research effort aimed at exploiting in any way, for military purposes, the energy associated with body motion and how to convert that energy to electricity.

Recent advances in the technologies relevant to harvesting human power, as presented at the workshop, suggest that unobtrusive systems might be built in the range from microwatts to a few watts. As the Army becomes more mobile, a premium is to be paid for capability, reliability, autonomy and minimal mass systems. The frontline soldier, more often than not, does not have access to energy for recharging his power sources and therefore, must carry all his required power sources to complete his mission. The ability to harvest human energy, if favorable in terms of reliability, size, weight, and energy efficiency might translate immediately into increased autonomy time, increased capability, reduce or eliminate certain logistics items, and, perhaps, reduced cost. Fieldable technology rarely equals laboratory prototype or theoretical capability. Obstacles sometimes are fundamental and perhaps can be finessed through appropriate R&D, innovative techniques, and skillful engineering. This workshop attempted to explore some of the possibilities. As confirmed by the plenary speakers and the working groups, there are a number of potential applications where harvesting of human energy could be applied. Typical are:

- Personal battery chargers
- Medical sensors
- Display power sources
- Gun sight power
- Rangefinder

This subject is certainly multi-disciplinary. For example, appropriate electrical converters must be combined with mechanical converters, which in turn must couple to the human body. Further, the need for non-interfering operation is paramount for acceptance. The ultimate utility of harvested energy may not reside in the fundamentals of the techniques used to harvest but in such issues as: can it be manufactured in mass from affordable materials; can it be made robust enough and provide the reliability needed to function in a hostile environment, can it be engineered into a package with minimal signature, can it be made non-interfering with the soldiers normal functioning, and will it provide an enhanced capability to the Soldier in the field.

As the workshop progressed, several pacing ideas emerged which were used to guide the workshop process. These are:

- There is a growing civil market for human powered systems with several products already available on the open market;
- It is only necessary to convert a small portion of the energy consumed as food by the soldier to power some applications.
- There does not appear to be any "fundamental physical reasons" why Human Powered Systems cannot be built with modest efficiencies;
- There is a definite lack of engineering experience with Human Powered Systems of the type of interest to the Military;
- A concerted program could produce laboratory devices for evaluation within 3-5 years.
- There are a large number of relevant disciplines such as MEMS, etc. which should have impact as the field emerges.
- However the energy is harvested, it must not interfere significantly with the normal activities of the soldier and must not impede his mobility.

Assessment of the State-of-the-Art of Human Powered Systems by Characterizing Techniques and Determining Their Applicability to ARMY/DARPA/Civil Applications

The amount of power associated with physical activity was estimated by the Workshop participants. The table below lists some estimates for the power levels associated with physical activity typical of that for the Dismounted Soldier.

Activity	Power in Watts
Sleeping	81
Standing at ease	128
Walking	163
Brisk Walk	407
Long distance running	1048
Sprinting	1630

The Workshop considered several potential sources of energy associated with the human body which might be utilized for conversion to electricity. The most promising are shown in tabular form below.

Source	Est. Max. Power available Watts	Maximum estimated Conversion efficiency
Body heat	116	~3% assuming total capture
Breath	1.0	40% based on turbine eff.
Blood pressure	0.9	about 2%
Upper limb motion	24-60	a few percent
Walking (heel strike)	67	PZT converter ~7% Generator ~50%
Body waste (urine)	1-5	Fuel cell ~ 50%

From the above, limb motion and the heel strike associated with walking and running are attractive potential sources of energy as long as the requirements are for levels of a few watts or less. The conversion mechanism will determine the level of power available for a given scheme. Since physical activity is inherently intermittent, it is necessary to have a storage mechanism. Rechargeable batteries, electrochemical capacitors, pneumatics, springs, and flywheels are candidates. Rechargeable batteries and electrochemical capacitors are the most promising with batteries offering higher specific energy and capacitors offering higher specific power. The energy density using spring metals is on the order of 0.4-1.0 joules/gram, making them an attractive candidate. Conversion to electricity still requires a generator of some sort. Numerous candidate mechanisms for harvesting heel strike and limb motion were discussed, however, the state-of-the-art is not advanced enough to determine their efficiency or ultimate utility. **Human powered shavers, radios, flashlights, watches, and night vision scopes are currently available on the civil market. All convert human motion to electricity to power the respective devices.**

Referring to the table above, the energy available from the human is in several forms. The workshop participants examined a representative sample of possible conversion mechanisms in order to analyze the advantages, disadvantages, and appropriate uses for each. The participants chose not to concentrate on conversion mechanisms for thermal energy due to the distributed nature of the heat source and its "low quality." The technologies examined in some depth were electrostrictive polymers, piezoelectric devices, electrostatic force arrays (also called integrated force arrays), inertial energy scavenging combined with a generator and storage element, fuel cells (based on use of urine), and electromagnetic generators.

Converter Mechanisms

Electrostrictive polymers: These materials were compared to piezoelectrics, although they function by harnessing the energy created when mechanical strain is applied to the material after dipole induction with a high voltage charge. They are more flexible than the piezoelectric polymer PVDF, and are capable of producing more energy (reasonable estimates suggest about 1-3 Watts). However, a large voltage (1000V) must be applied to the polymer to get electrical energy out when mechanically stressed. A battery and an appropriate high voltage power supply must accompany any system design. The large voltages inherent in this approach to conversion also creates the requirement for power conditioning from approximately 1000V down to 10V (output), possibly creating an undesirable EM signature in the conversion process. The energy from Electrostrictive polymers comes from a very large change in area (approx. 200%) and a large strain to the material (approx. 100%). Such deformation may impact the durability of the material, as well as affecting the surrounding device. The use of this material for harvesting power has not yet been demonstrated, i.e. no prototype device of this nature has been built or tested.

Piezoelectric devices: Piezoelectric materials generate electrical energy from mechanical strain, like Electrostrictive polymers, but do not require the application of a high voltage since they possess a permanent dipole moment. Piezoceramics were not considered, in detail, because of their fragility and the need for a hard strike to generate mechanical strain. The polymeric piezoelectric material PVDF is more promising, but lacks the elasticity of electrostrictive polymers, making it difficult to generate the amount of mechanical strain needed to produce a significant amount of power. Conservative estimates suggest that with current technology, piezoelectric devices would only be useful for low power applications, in the 10-20mW range. However, the requirement for power conditioning is much less than for electrostrictive polymers (from 100V down to 10V) and there is no need for a battery to provide a bias voltage. PVDF is also a well characterized material and prototype devices have been created.

Electrostatic force arrays: (Also called Integrated Force Arrays) This technology is in the very early stages of development and relies on mechanical strain and voltage biasing much like the electrostrictive polymers. It has the advantage of being able to be sized for a particular application, using MEMs technology for mW power demands and mesostructure design for power demands in the range of watts. Cost is an issue and the manufacturing process is still under development. There are also issues of durability. The use of this material for harvesting power has not yet been demonstrated, i.e. no prototype device of this nature has been built or tested.

Inertial energy scavenging: This technique was based on the paradigm of the "Seiko watch mechanism", using displacement of a proof mass to drive a small generator. The electrical energy produced is stored in a small battery or capacitor which consequently drives the watch mechanism. The level of energy that can be obtained from this approach by conservative estimates is in the mW range, but there is no proof of concept for devices that deliver more than a few microwatts. However, the design and engineering of such a system is further along than the systems based on the converters described above. In the microwatt range, this technique is well characterized and commercial products are available.

Urine-based fuel cell: A fuel cell based on the hydrolysis of urine to generate urea is, in principle, possible. The individual elements of the converter system, such as enzymatic hydrolysis of urea to carbon dioxide and ammonia, and oxidation of ammonia to nitrogen and water, have been demonstrated, but no working prototype for the whole fuel cell yet exists. One problem with the system is the need for alkaline conditions that may require transport of sodium hydroxide, a hazardous compound. Also, to achieve power generation in the range of 0.5 - 1W, a system to concentrate the breakdown products of urea, such as reverse osmosis, will be necessary. One attractive feature of this fuel cell concept is the production of water as a by-product of the system.

Electromagnetic generator: Two different systems were discussed within the workshop context, with different types of energy input - i.e. using conventional gear trains and using a hydraulic or pneumatic system. In both cases, however, the goal is to generate power in the range of 3W, taking advantage of our large muscular groups (such as in the legs) and simple motions against gravity. There is a wealth of material and applications for small DC permanent magnet motors. These units can be "run backwards" to produce a small generator. Typically these generators are less than 80% efficient while larger devices, designed as generators, are greater than 90% efficient. There is little or no efforts within the scientific community to design efficient small generators of the type needed for harvesting of human energy. Several commercial products are available which utilize these small generators in a human powered mode.

While intriguing, the state of the art for conversion mechanisms is such that it is impossible to estimate military system performance in units such as W/kg.

Within the numerous organizations interested in Human Powered Systems, there is a wide range of individual components whose principles have been demonstrated on the laboratory scale that would appear to be ready for rapid maturity if the applications are real. Examples of intermediate storage units include flywheels, springs, electrochemical capacitors, phase change materials, and shape memory alloys. To date, a few of these components have been assembled into laboratory systems which indicate feasibility and provide marketable products. The most prominent examples which can be purchased are the Seiko electric watch and the "wind-up radio" from Baygen. Numerous examples of storage mechanisms were discussed within the workshop, the most promising are discussed below.

Energy Storage Technologies

High Rate Rechargeable Batteries. The state of the art in high rate rechargeable batteries was discussed at "Power '97." In general, very thin lead acid cells can have specific power levels on the order of 10 kW/kg in sizes comparable to "D" cells. The Lithium technologies can provide specific power levels in excess of 1 kW/kg if specially designed. The trade off for high specific power in batteries is decreased specific energy and much reduced life. At the high rates, the useful specific energy is diminished by factors of 3-5 over that for normal operation. Typical specific energy for rechargeable batteries is between 40 and 100 Whr/kg, with the larger number being associated with large cells and normal discharge rates. Appropriate batteries for use in harvesting and storing at modest rates exist in a multitude of sizes ranging from button cells to large packs made up of many cells in series/parallel arrays. The technology is mature with numerous suppliers in a multitude of chemistries and sizes. Due to reduced cycle life, high specific power batteries may not be appropriate for harvesting and high specific energy batteries may have to be used in conjunction with other technologies(if power is an issue) in human powered systems.

Electrochemical Capacitors. High rate electrochemical capacitors are just now emerging from the laboratories. In general, devices based on aqueous electrolytes can have specific power in excess of 15 kW/kg with excellent scaling to small sizes. Specific energy is usually factors of 5-10 less than batteries but comparable to "high rate" batteries. The best specific energies for electrochemical capacitors are in the range of 5-15 Whr/kg, with the higher number being laboratory prototypes. Cycle life in excess of one million has been demonstrated in several embodiments. Devices based on hydrous amorphous ruthenium oxide, invented at the Army Research Laboratory, offer the best promise for high specific energy and specific power. The mechanisms and control of leakage currents are not well understood. There are several manufacturers of both prototype and commercial devices which could be used in demonstration systems.

Springs. Springs have been used for decades as intermediate energy storage mechanisms. All of these materials store energy due to reversible elastic distortion, with the amount of energy stored proportional to the distortion. In general, the specific energy is on the order of 0.1-0.3 Whr/kg. Note that when the energy stored in a spring is retrieved, it is "mechanical" in form and requires conversion to electrical format. Spring technology is mature and it is doubtful if the specific energy can be increased significantly without compromising life and safety. There are numerous manufacturers who will custom design to specification. Springs form the storage mechanism for the "wind-up" radios from Baygen.

Inertial/Flywheels. Flywheels are a well established method of inertial energy storage. In large sizes, flywheels are mature and form an integral part of many advanced systems. The amount of energy stored in a flywheel is proportional to the mass and physical dimensions(moment of inertia) and the angular velocity at which the flywheel is spinning. In modest sizes, energy storage densities approach that of batteries (>50 Whr/kg) but much of the advantages are lost in small sizes due to poor scaling of windage, bearing, and friction effects. Further, flywheels have large gyroscopic effects which tend to interfere with an individuals freedom of motion. The technology is mature and there are numerous manufacturers who will custom design to specifications. Energy is retrieved in mechanical form requiring the use of a mechanical-electrical converter.

Gravitational. Storage of energy in the gravitational field of the earth is also a well established art in many forms. Pumped hydroelectric, "pile drivers," and grandfather clocks are classical examples. From the perspective of human energy harvesting, the energy density is proportional to the amount of mass that a human can lift and the distance within the field that he can lift the mass. The work done lifting a 100 kg mass 2 meter against the earth's gravitational field results in 2000 joules being stored in the mass. In mechanical form, this energy can be retrieved with high efficiency making the energy storage density on the order of 20 joules/kg(mechanical), a rather low specific energy. Utilizing the appropriate converter, approximately 1.5 watts could be retrieved for 1000 seconds with each repetitive lifting of the mass. Power is converter specific and higher rates can be achieved for shorter times.

Identify the Key Research Issues Pacing the Development (or Limiting Full Development) of Efficient, Human Powered Systems

The state-of-the-art is such that useful devices can be built with existing technology. The consensus opinion was that it is feasible to harvest some of the "waste" energy from a soldier, however, that does not answer the question of practicality or desirability. The research and development issues necessary to make these judgments can be divided into those which effect the human in the system, the materials technologies of the converter/storage technologies, their operating environmental response, and those which influence the manufacturing/packaging technologies. The research issues associated with the human in the system are:

- What source on the human do we tap into
- How do we tap into the source unobtrusively
- What is the effect on the human performance as a result of harvesting
- What are the human metrics to be employed in evaluating harvesting
    - Physiological factors
    - Psychological factors
    - Body morphology
    - Field experience by soldiers

- Missions/work profiles

Numerous converter technologies were discussed within the workshop. The most promising have numerous research issues associated with their development to the point of optimum performance. Research issues associated with the most promising converter candidates are:

Mechanical to Electrical - Generators

- There is an enormous "impedance" mismatch for miniature generators. Generators operate efficiently at high rpm but the human input is orders of magnitude slower necessitating high gear ratios or unique hydraulic systems.
- For geared systems, loss mechanisms get worse as the systems become smaller.
- For generators, the design rules and physics are well known but not widely applied to small systems. State of the art for small motors is mature. Technology is relevant but not totally transferable.
- New magnetic materials may impact design rules.

Mechanical to Electrical - Piezoelectric and Electrostrictive

- Optimum coupling coefficients
- Adaptive ensembles of elements
- Compliant electrodes
- New materials
- Fatigue properties/cycle life

Thermal to Electrical

- While there is ample energy, the temperature at which the energy is available is low and consequently the delta T over which thermoelectrics would function is small.
- Energy is distributed over the surface of the human. How do you capture the available energy without disturbing core body functions?
- New thermoelectric materials are needed to have any reasonable hope of utilizing waste thermal energy (DARPA has programs in this area).

Chemical to Electrical

- Biofuel cells not well developed or characterized
- Scaling of composters and digesters and methods of speeding up the processes
- Appropriate catalysts

The research issues associated with storage technologies are:

Electrochemical

- Improved low temperature performance
- Internal loss mechanism understanding and mitigation
- Ruggedization

- Manufacturing technology

Inertial

- Miniature bearings
- New materials
- Miniature gear mechanisms
- Loss mitigation

Mechanical/Springs

- New lightweight spring materials

Gravitational

- Methods for implementing

Identify the Major Limiting Factors Which Must Be Addressed as Part of Overall Human Powered System Design

From the perspective of the Dismounted Soldier potential applications, as described within the workshop working groups, should be scrutinized from the viewpoint of desirability, probability of successful development, and potential impact to the Soldier if successful. From an Army perspective, cost, reliability, maintenance, power capability, energy storage capability, human non-interference, etc., are key issues to any large scale introduction into the inventory. The appropriate technologies are immature for Army applications and as such it is difficult to assess how successful human powered systems will be and how well they will function in the Army environment. All of the equipment for the Dismounted Soldier must be enormously compact and rugged. Consequently, issues such as energy density, power density, minimal signature (both thermal and acoustic), orientation-independence, ruggedization, simplicity of operation, and reliability are the major limiting factors from an operational point of view. Cost is always a limiting factor. These limiting factors translate to the materials issues discussed above as critical research issues. Since human powered systems are just beginning to emerge, there is little data which can be used to judge performance within system configurations. These limiting factors are critical and a data base must be established before any meaningful applications scenarios can be evaluated. The limiting factors are:

- Amount of energy which can be harvested without becoming a load factor for the soldier
- Interference with the normal functioning of the soldier
- Absolute power levels needed for powering the electronic suites
- Reliability in a battlefield environment
- Integration into the soldiers battle dress
- Distribution System

Prioritize Research Issues, Indicating the Impact if Research is Successful

The following are typical of the tasks which could impact human powered electrical systems:

- Efficient lightweight intermediate storage units, optimized to the particular harvesting technology employed
- Analysis of the motion of humans when doing routine tasks and how to couple converters to this motion in an unobtrusive manner
- Laboratory prototypes employing small electromechanical converters and piezoelectric devices
- New converter technologies

Human Powered Devices are at a stage where there are modest commercial successes as witnessed by several products with wide scale availability. The workshop unanimously agreed that the technology exists to allow demonstrations of potential to Army applications. Many of the components necessary to build a significant system have been demonstrated separately. There is sufficient capability in several R&D organizations to build prototypic systems which could be evaluated in the field. Only in that mode can priority R&D issues be identified within the framework of application. Research is needed to accurately characterize the capability of each system concept within the framework of the application to the Dismounted Soldier. The successful application of human powered systems must result in weight savings, cost effectiveness, added capability, and reliability. At the component level, the priorities are:

- Demonstration of a human powered system designed for a specific Army task
- Development of optimized storage and converter technologies, and;
- Integration of the system into the battle dress of the dismounted soldier.

Provide Milestones for Research Teams to Attain to Assure Significant Improvements in Human Powered Systems Technology Over a Near-term and Long-term Development Program

The workshop participants identified several potential applications for the Army. The most promising were:

- Personal battery chargers in the "few watt" category
- Stand alone power for medical sensors, some displays
- Utilizing the appropriate high power intermediate store, high power burst mode communications/data transmission
- Combination exercise/generator devices for the special forces

Given sufficient funding, the technical community should be able to produce prototypic devices for evaluation within three years. An engineering prototype could be built within one year thereafter. The most promising devices appear to be those which would harvest energy from the "heel strike" or utilize gravitational energy in the same mode as the "grandfather clock" for battery charging. For medical sensors, the "Seiko clock" mechanism is ready to apply in the microwatt range.

Identify Operational/environmental Constraints Such as Materials, Signatures, Manufacturing, and Pollution Which Might Influence Applications or Improvements Envisioned

Within the framework of the Workshop, the participants identified the following operational constraints due to the peculiar nature of the requirements for the Dismounted Soldier:

- Human powered systems must not have a signature which can be exploited by a hostile force
- Human Powered Systems must be capable of orientation independent operation in many scenarios
- Human Powered Systems must be robust and capable of sustaining mechanical shock typical of that associated with the battlefield environment, and
- Human Powered Systems must offer an operational advantage over current methods of supplying electrical energy to the soldier
- Human Powered Systems must offer minimal interference to the normal operational mode for the soldier

It was the general consensus of the participants that Human Powered Systems shows substantial promise as useful power sources for both civil and military applications. It is not possible to judge the ultimate utility or the degree to which these devices can replace current technology. Clearly as the levels of energy and power needed by the soldier diminish, human powered systems become more feasible, desirable, and perhaps practical.

INTRODUCTION

Prospector IX is the ninth in a series of workshops dealing directly with advanced technologies applied to the individual soldiers needs. Technology projections for the energy demands for electronic systems relevant to the Dismounted Soldier, as discussed in the NRC report "Energy Efficient Technologies for the Dismounted Soldier," 1998, suggest that some of the energy necessary to power the soldiers electronic suite might be harvested from the individual. As the Army becomes more mobile, a premium is to be paid on autonomy, reliability and minimum mass systems. Improvements in power technology and systems in terms of reliability, cost and maximum energy/power density translate immediately to increased capability and reduced cost. Human Powered Systems could have major impact by providing essentially unlimited autonomy time for the electronic systems in the field. Further it should simplify or eliminate certain items from the logistics chain.

In November, 1990, the first workshop on Mobile Tactical Battlefield Power Technology was held at the request of the Army Research Office. One of the major findings from this workshop was the need for research and development to improve the Army power technology at the low end of the scale. Power technology up to about 500 W and man portable is absolutely key to the effectiveness of the Armies mobility. Further, issues of autonomy time, reliability, scaling and cost were not clearly defined and pointed to the need for other workshops dedicated to subsets of the Armies power needs. The second power workshop on key issues in Electrochemical Power Technology was held at the Auburn University Hotel and Conference Center on May 27 - 28, 1992. That Workshop was requested by the Department of the Army, Assist. Secretary of the Army for Research, Development and Acquisition (ASARDA), and was sponsored by the Army Research Office. The focus for that workshop was the peculiar challenges for power technology associated with the Soldier as a System and the ability of electrochemical power sources to meet the requirements. The enormous energy stored in the nucleus is an attractive source if means can be invented to access this energy in a cost effective and environmentally safe way. To assess this technology, Prospector II studied Radio isotope powered (RTG) systems with emphasis on whether they could meet any of the Army's needs. Since small combustion driven engine-generator systems also appear capable of performance within the requirements for the soldier system, the focus of Prospector IV was on the capability of these small engine-generator systems and the problems which must be solved prior to placing in the inventory. Within the scope of the Soldier as a System, there is a wide range of power requirements depending upon the mission duration and the capability needed for the mission. At Prospector IV, it was pointed out that there was a new and emerging technology of miniature machines or "systems on a chip" which could be applicable to all of the technologies discussed in the Prospector series of workshops and further, might provide new capability. For that reason, Prospector V explored the application of "MIMS" technology to Army needs with special emphasis on the Soldier System. Prospector VII focused on small fuel cells which are even now being evaluated for use in a battlefield environment. If fueled systems are to be introduced into the inventory, it would be desirable to have them function on the current battlefield fuels. Since ThermoPhotoVoltaics(TPV) is emerging and could use battlefield fuels, a workshop, Prospector VIII, was held to assess the potential of TPV and to put its attributes in perspective with respect to competitors such as batteries, fuel cells and small motor-generator sets. If the energy demands for the electronic suite for the Dismounted Soldier decrease substantially, it becomes possible to harvest some or perhaps all of the energy from the waste energy available from the soldier himself. Hence Prospector IX was held to examine the potential of Human Powered Systems. *The goals of the workshop were to draw the participants' attention toward three major sets of criteria -- requirements, key research issues, and projected capabilities and development opportunities.* The specific goals, as determined by the Board of Directors, are to:

- Assess the state-of-the-art of human powered systems;

- Characterize innovative technologies which might be relevant;
- Identify the key research issues pacing the development of efficient human powered systems;
- Identify the key issues which must be addressed as part of overall human powered system;
- Distinguish the limitations imposed by technology from those imposed by nature;
- Establish parameters for the consistent evaluation of human powered sources within an overall system concept for comparison with other technologies;
- Identify the power conditioning technologies appropriate for matching human powered systems to loads within the constraints of cost, weight, and volume;
- Identify the power/energy regimes for which human powered sources are applicable;
- Identify the physiological limits to the human to power systems.

To accomplish these goals, a group of scientists and engineers, active in relevant technologies, were invited to present current perceptions of the state-of-the-art in Human Powered Systems and the relevant technologies. A plenary session was organized to present a government and industrial perspective on needs and possible scenarios which might benefit from human powered devices. The plenary agenda is shown in figure 1.

OVERVIEW SESSION - 1

Chairwoman: Dr. Donna Cookmeyer

- "Soldier System in 20 Years", Robert O'Brien (NATICK)
- "Future Power Requirements for the Dismounted Soldier", Rudolf Buser (CECOM)
- "Power for the Dismounted Soldier - A Summary of the NRC Study", Frank Rose (Auburn)
- "DARPA Perspective on Power Technology", Bob Nowak (DARPA)
- "Special Operations Perspective", Sal Raineri (Special Forces)

OVERVIEW SESSION - 2

Chairman: Dr. Dick Paur

- "SUO Power Profiles - CECOM Perspective", Jim Stephens (CECOM)
- "NASA Investment in Spacecraft Systems Technology", Joe Sovie (NASA LeRC)
- "Rudimentary Physics of Man-Powered Systems", Art Ballato (CECOM)
- "History and Status of Personal Power Devices for the Commercial Market", John Hutchinson (BayGen)
- "Physiological Factors that may Limit and Techniques that may Enhance Human Performance", Ellen Glickman-Weiss (Kent State University)

Figure 1.

As confirmed by the plenary speakers, the interest in novel power technology and its application to the soldier is high and that it appears possible to develop numerous human powered systems both for commercial and military applications.

To accurately determine the utility of human power, it is necessary to attempt to define the state-of-the-art in the relevant technologies. Therefore, to assist in the workshop process, scientists and engineers, active in relevant technologies, were invited to present technology summaries describing the state-of-the-art, near-term-state-of-the-art and give their opinions of ultimate limits with some considerations for practicality. The agenda for the technology sessions is shown in Figure 2.

TECHNOLOGY SESSION - 1
Chairman: Dr. Bob Nowak

- "Electrostatic Integrated Force Arrays", Scott Goodwin-Johansson
- "Energy Conservation and Alternative Energy Sources for Wearable Electronics", Dan Siewiorek (Carnegie Mellon"
- "Energy Storage/Conversion Materials", Ralph Zee (Auburn)
- "Electrochemical Capacitors", Steve Merryman (Auburn)
- "Compact and Lightweight Energy Conversion using Electrostrictive Polymers", Roy Kornbluh (Stanford Research Institute)
- "Lunar/Mars Space Suit Requirements", Anthony Wagner (NASA/JSC)

TECHNOLOGY SESSION -2
Chairman: Dr. Steve Merryman

- "Integrated Power Management for Microsystems" Dwayne Fry (ORNL)
- "Seiko Human Powered Quartz Watch" Seiko - Epson Staff
  - Overview — Masakatsu Saka
  - Details of the Device — Kinya Masuzawa
  - Applications of AGS — Kinya Masuzawa
- "Overview of Developments in South Africa" Etienne Rijkheer (Syzygy)
- "Technological Challenges for Human Powered Systems" Eric Tkaczyk (GE)

Figure 2

The remainder of the workshop was spent in small working groups centered around:

- Potential Applications, Specific Mission Needs, State-of-the-Art
- Key Research Issues, Major Limiting Factors, Constraints
- Strategies & Technologies, Priorities, Near & Long-Term Developments, Milestones to Achieve Priorities

In a final session, the working group chairman presented a summary of their group's deliberations and findings to the general assembly of participants. As usual, considerable lively discussion attended each report and was incorporated as accurately as possible in the executive summary results.

The 45 participants were drawn from Industry (15), Academia (10), and Government laboratories/National Laboratories (20) and represented an adequate cross-section of scientists and technologists working, or interested, in the field or in relevant technologies. The remainder of this document is a collection of the workshop presentations and summaries from the working groups.

WORKING GROUP DELIBERATION SUMMARIES

WORKING GROUP 1 SUMMARY

Group 1: Applications

Members

Henry Brandhorst, Chair
Carolyn Bensel
Tom Davies
Tom Dolgaskei
Dwayne Fry
Mary Hendrickson
Jack Kruger
Gerald Lebau
Lionel Levinson
John Munroe
Dick Paur
Sal Raineri
Dan Siewiorek
Ikyo Tokunaga
Kevin Toomey, Recorder
Tony Wagner

Group 1: Applications

Charge:

- Assess how the energy will be taken from a human
- What are the converter options?
- Is energy storage necessary?
- Power/energy level achievable - near term and far term
- System Concepts
- What components need to be developed to implement system concept

Power Sources

Kinematic	*Thermal*	*Chemical*
Breathing; 0.4W	Delta Temp.	Waste Products
Arm Motion	Clothing	CO_2
Leg Motion		Sweat
Hand Motion		Urea
Heart Beating; mW		Digestive Juices
Heel Strike; 4-5W		
Clothing/Equipment;		
Jaw Motion		
Parachute Landing		
Blood Pressure		

Storage Media

Batteries

Capacitors

- super
- ultra
- electrolytic

Mechanical

springs
flywheel
gas pressure
(gravity/mass)

Thermal

phase change

Chemical

fuel cell

electrostatic

magnetic

Generation (mechanisms)

- Brain Energy
- Electromechanical
  - motor generator
  - weight
- Piezoelectric
- Electrostrictive
- IFAs
- Microturbines
- Bimetallics

Applications

21 Day Mission

Face shield Display
Voice activated
IR2/ NVG
Thermal
UV Visual
Magnification 2x
Situation awareness

- maps
- overlays
- mine fields
- photography
    - face recognition
    - machinery

- system performance; weapon status
- medical status; other members

18 month panel came up power estimates for NRC 2015
Frank Rose can get the report;
Report is currently being reviewed.

Face Shield Display ≈ 2W

Power generator
hand generator soa= 25J
rotary pull)

Classes of Applications Considered

1 W continuous, 10 W peak (seconds)

2 Watts, 5 hr.

mW continuous

Types of Power for Applications

Application	Concept	SOA (State of Art)	Issues	Risks
1W,10W for sec.	Hand Crank Gen (axial gap) Capacitor battery	???	Weight Fatigue Noise	Medium
1 W, 10 W for sec.	IFA Capacitor Battery	218 cm^3 ???	Size Weight Temperature High Voltage range of movement Location	High

2W for 5 hrs	Electrostrictive Battery	0.7w-s/cm^3 5w-s/step	Power Condition/ conversion Life cycle Strength Shapeability	Medium/Hi
2 W for 5 hrs	Microturbine (shoe)	none est. electrostr.	maybe impractical Space life cycle fatigue	High
2 W for 5 hrs	UREA / FC	???	Eff. -→ NH_3 membrane bacteria life signature temperature personal hyg.	High

mW continuous	Mech. Gravity battery	Seiko watch	Scalability signature weight Efficiency Battery	High
mW continuous	Themoelectrics	zT=1 eff. <1%	Efficiency MTLS Foot print Body Temp ↓	High

mW continuous	UREA→ NH_3 Fuel Cell	NH_3/Air	Eff. -→ NH_3 membrane bacteria life signature temperature personal hyg. Residue Duty cycle	High
mW continuous	Electrostrictive Capacitor (Flexible waterproof)	0.7w-s/cm^3 5w-s/step	Charging Source Strength High Voltage Decay Breathability Abrasion	Medium

mW continuous	“Leg Brace” Electrostrictive Capacitor (Flexible waterproof)	0.7wS/cm^3 5wS/step	Charging Source Strength High Voltage Decay Breathability Abrasion	Medium

Overarching Question

Where is the breakpoint in human energy?

- Carrying Dead Batteries - vs Generating Power/Energy

WORKING GROUP 2 SUMMARY

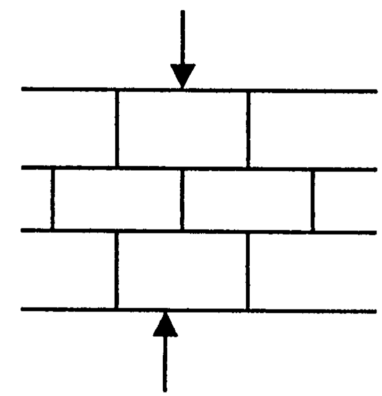
Technology Working Group

Discussion Summary

- Piezoelectric harvesters
- Electrostrictive polymers
- Integrated Force arrays
- Inertial scavengers

11/5/97

Electrostatic Force Arrays

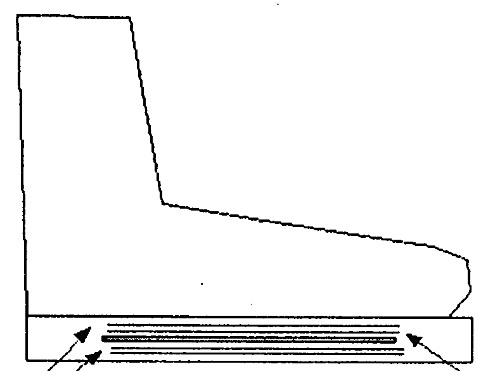


- Conversion Technology
  - ΔC from deformation alters Q/V
    - Like condenser microphone
    - Collect power over mechanical cycle
    - Microstructure
    - No dialetric/electrostrictive material between plates
- Modes: Compressing/Pulling
  - Feet, clothing (limb motion, breathing), Backpack…
- Energy density: 200 cm^3/W
- Issues
  - Must bootstrap with battery & condition output voltage
    - MEMS: 100 V -> 10 V
    - Mesostructure: 1000V -> 10V
  - Manufacturing and cost
  - Yield
  - Survivability, durability
  - Not yet demonstrated!

Electrostrictive Polymers

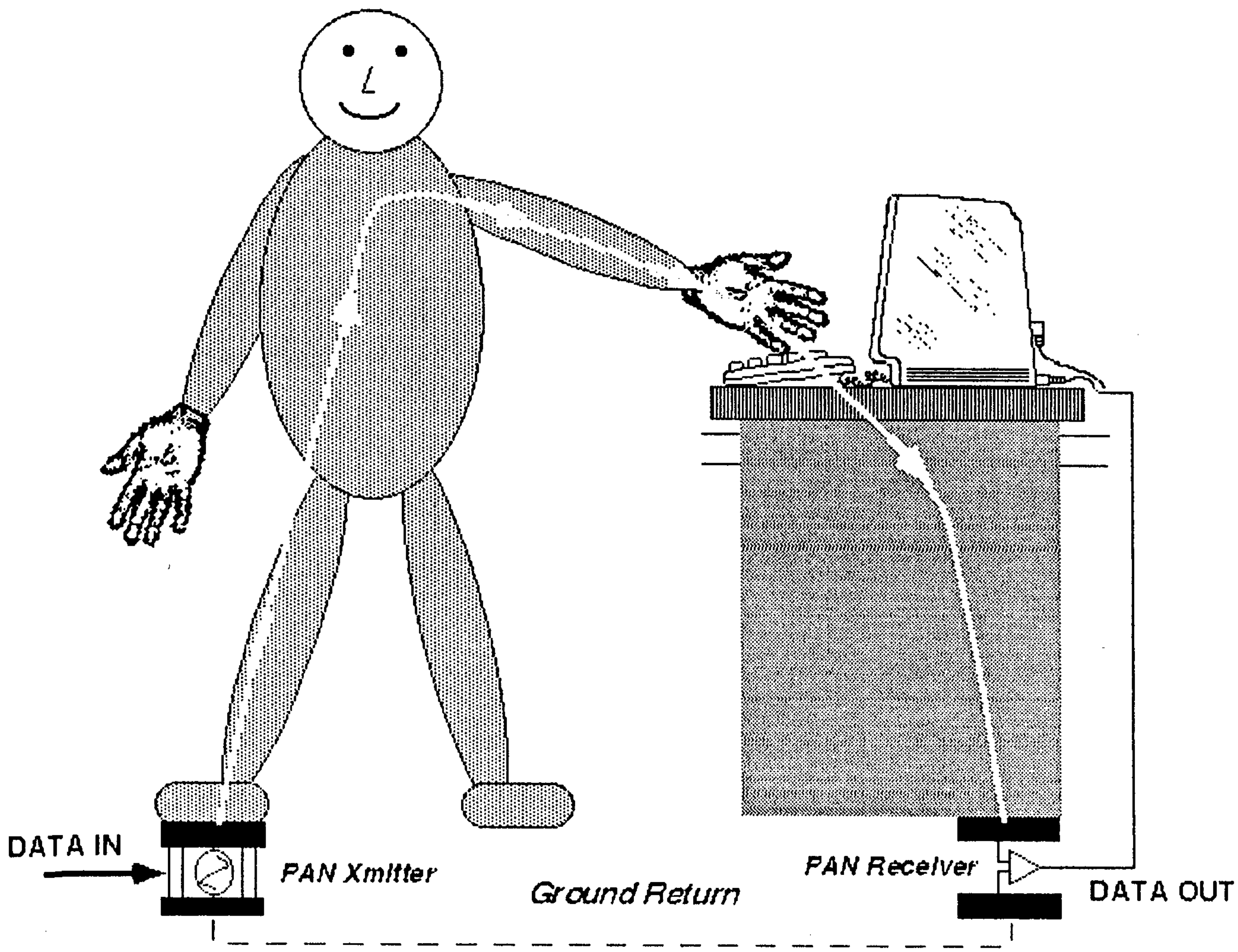
- Conversion Technology
  - Induced dipoles in electrostrictive material rotate w. strain
    - Collect power over mechanical cycle
  - Aim for 200% change in area, 100% strain
    - 10 cm^3/W
    - 10-20% Viscoelastic losses
- Modes: Compressing/Pulling
  - Heel/foot strike, clothing (limb motion, breathing), Backpack straps…
- Potential Energy Production: 1-3 Watts
- Issues
  - Geometrical problems with large deformation
    - Materials, electrode surface, implementation, durability
  - No piezo coefficient; need large voltage across plates
    - 1000 Volts discussed in examples
      - Breakdown?
    - Must bootstrap with battery system
  - Large step in power conditioner
    - 1000 Volts raw -> 10 Volts out
    - EM signature in conversion process?
  - Not yet demonstrated!

Piezoelectrics



- Conversion Technology
  - Force -> Piezoelectric charge -> Voltage
    - Don't need bootstrap battery
  - Ceramics, crystals impedance mismached
    - Prefer hard strike, fragile
  - PVDF foil applicable
- Modes: Pulling (exploit 3-1 mode)
  - Feet, Backpack straps(?)
- Energy: 20 mW
  - 4-ply laminate of 90 micron 25 cm^2 sheets, 2% strain, circa 1 Hz
  - Calculated by Toda @ AMP for shoe insert
  - Estimates range 10-100 mW/cm^3
- Issues
  - Low Power capacity
    - Difficult to pull multilayer foil at high strain
    - Trickle-charge, low-SS power applications
  - Interferes very little with sole, foot motion
  - Little/no mechanics, proven materials
  - Power conditioning: 100 V - 10V
  - Ongoing work by AMP and MIT; prototype soon
  - HyperElastic piezo polymer (FE Xtals in LC matrix)??

PAN Touch Communication



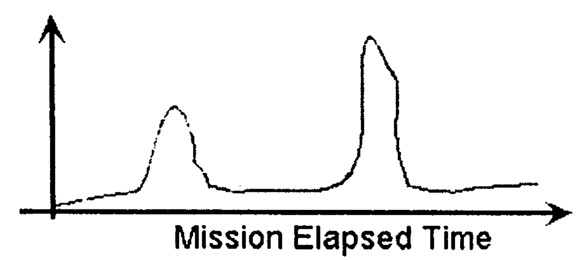
Note: PAN transceiver can be embedded in PC keyboard

Inertial Energy Scavenging

- Conversion Technology
  - Displace Proof Mass with casual motion
  - Demonstrated in Seiko watch
  - Best to pump mechanically resonant system (e.g., pedometer)
- Modes: Anything
  - Feet, arms, legs, backpack, tools
- Energy levels
  - Seiko device is order of a millwatt
    - 20-50 mW per device estimated possible; can do better w. resonance?
- Issues
  - Application in trickle-charge, distributed systems
  - Could be inefficient wrt. Power density (proof mass needed)
    - Exploit existing gear (backpack?) as proof mass
    - Ergonomics, irritation level
  - OmniMode device?
    - Wear for parasitic power, strap on crank for direct conversion

Load and Charging Management

- Large disparity between average and peak loads
  - Mission dependent
    - e.g., special forces vs. infantry in battle
  - Impacts designs and choices for power sources
  - Load management critical
    - Consumers sleep until needed
    - Significant power needed only during brief "bursts"
    - Distributed vs. centralized
      - Low SS. Power requirements in each system
      - Independent harvesters (no wires…)



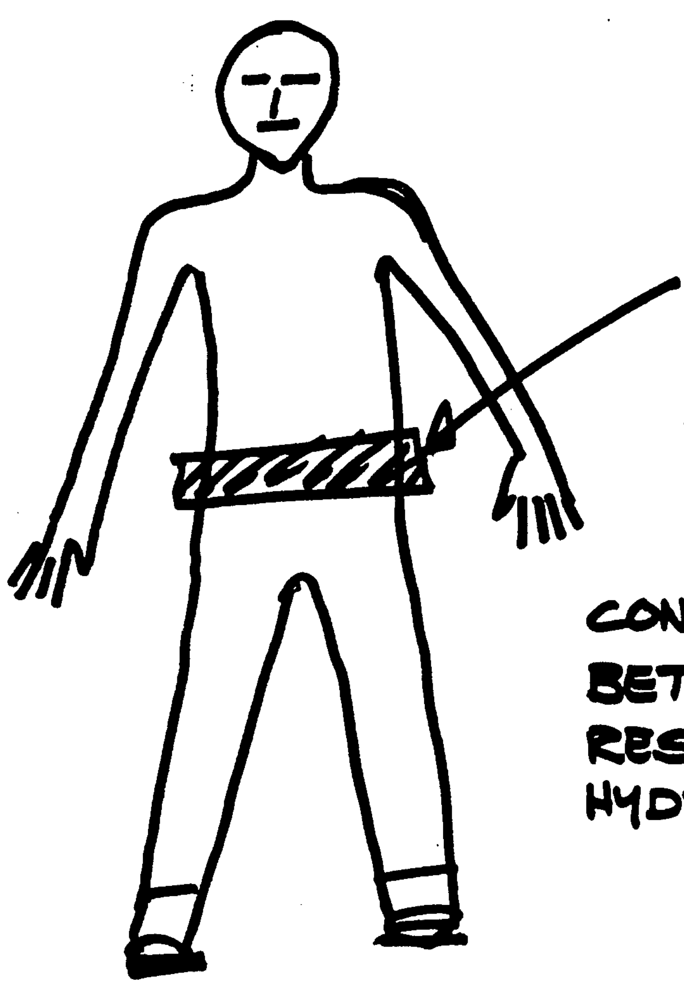
- Analogous situation with charging
  - Batteries, large capacitors don't want to charge fast
    - ESR losses, etc.
  - Continuous trickle-charge w. low-output electrical source
  - High-impulse mechanical input buffered, then metered out
    - Wind spring, lift mass, etc.

Electromagnetic Generator

Energy Input	Energy Distribution	Conversion	Conditioning	Storage	Key Issues
Heel Strike	Boot plugs into pant leg	Transfer of Fluid/gas drives motor	Generator needs to be at about 10 V to absorb 3W with low loss	Batteries	Brief high level work must be buffered to keep resistive losses down
Exoskeletal braces	Battery charger on belt				
Breathing	Constant dia belt with flex "baggies" on inner and outer surfaces	Pawl drives sawtooth gear, winds spring that smooths out power flow			Continuous, low level work is OK as is.
Lifting Back-Pack against Gravity	Hang Backpack on tripod. String unwinds				Generator needs high speed
Sit on chair that sags		Winch or rack-pinion drives gen.			Viscous losses versus gear friction
Rocking chair/ Rowing Mach					

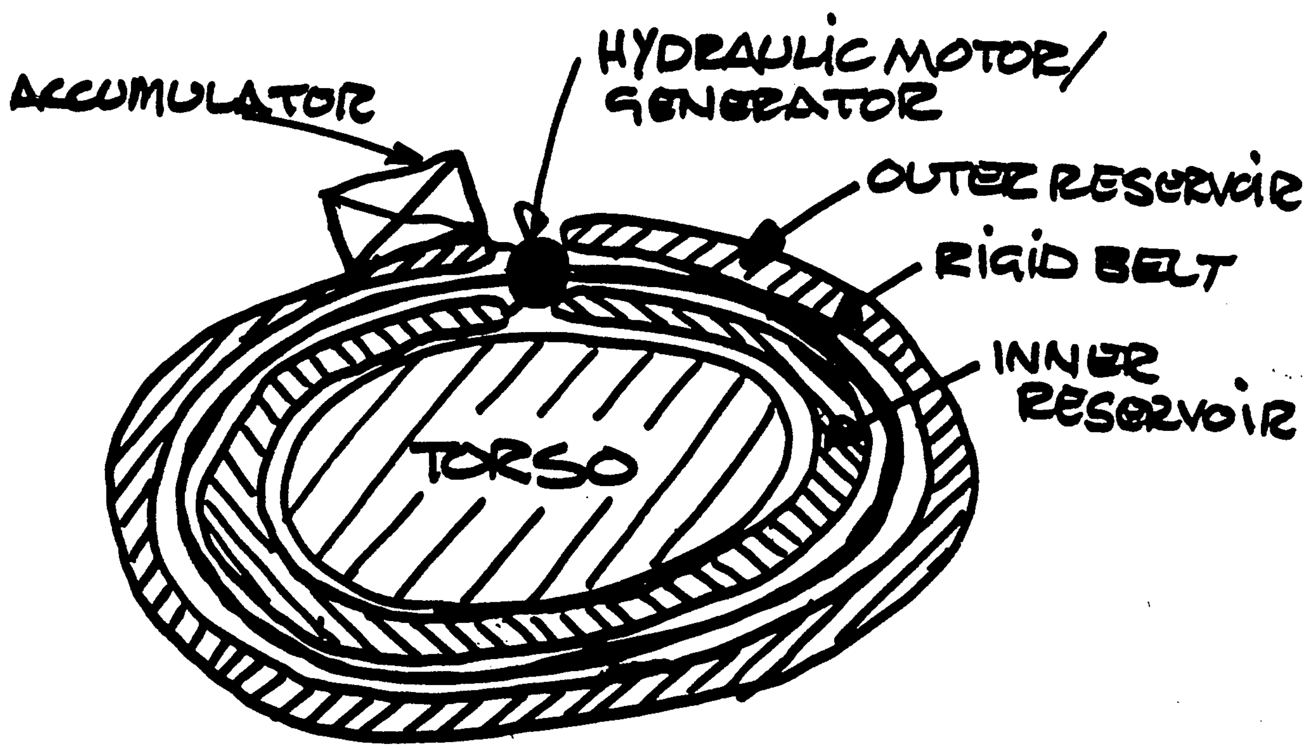
Waste Product Fuel Cell

Energy Input	Energy Distribution	Conversion	Conditioning	Storage	Key Issues
Human Waste Watt Range .5 - 1 Watt	Fuel cell based on urine. Urea is broken down to NH_3 by bound enzyme, NH_4OH drives fuel cell Human → 12 gm of urea/day $\rightarrow 2NH_3 + O_2 \rightarrow N_2 + H_2O$ 0.1M→1M Reverse Osmosis ~1V, 2W continuous by 1 human waste	None Correct voltage & current	Individual steps have been demonstrated to work Electrode size needs to be determined	"Fresh" supply every day	Needs alkaline environment NaOH is a hazard Full system has not been demonstrated

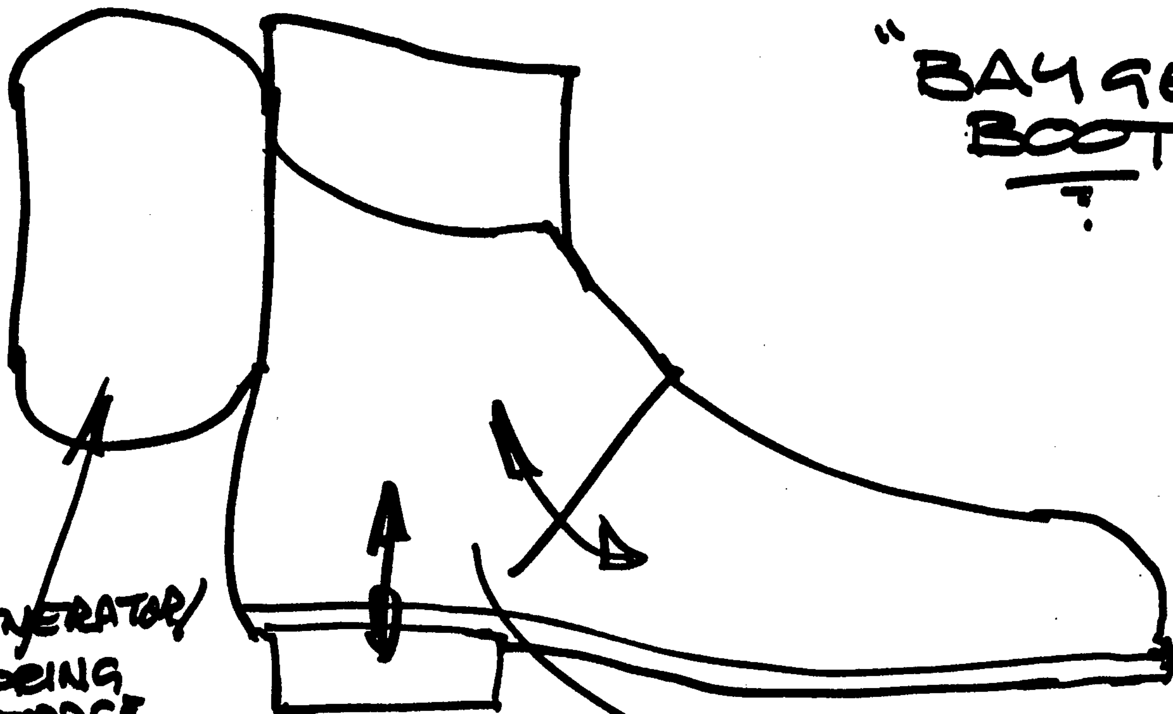


"HYDRAULIC BELT
WORN ON UPPER
ABDOMEN.

CONCEPT: FLUID FLOW
BETWEEN INNER & OUTER
RESERVOIRS THRU'
HYDRAULIC MOTOR/GEN.



"BAYGEN"
BOOT



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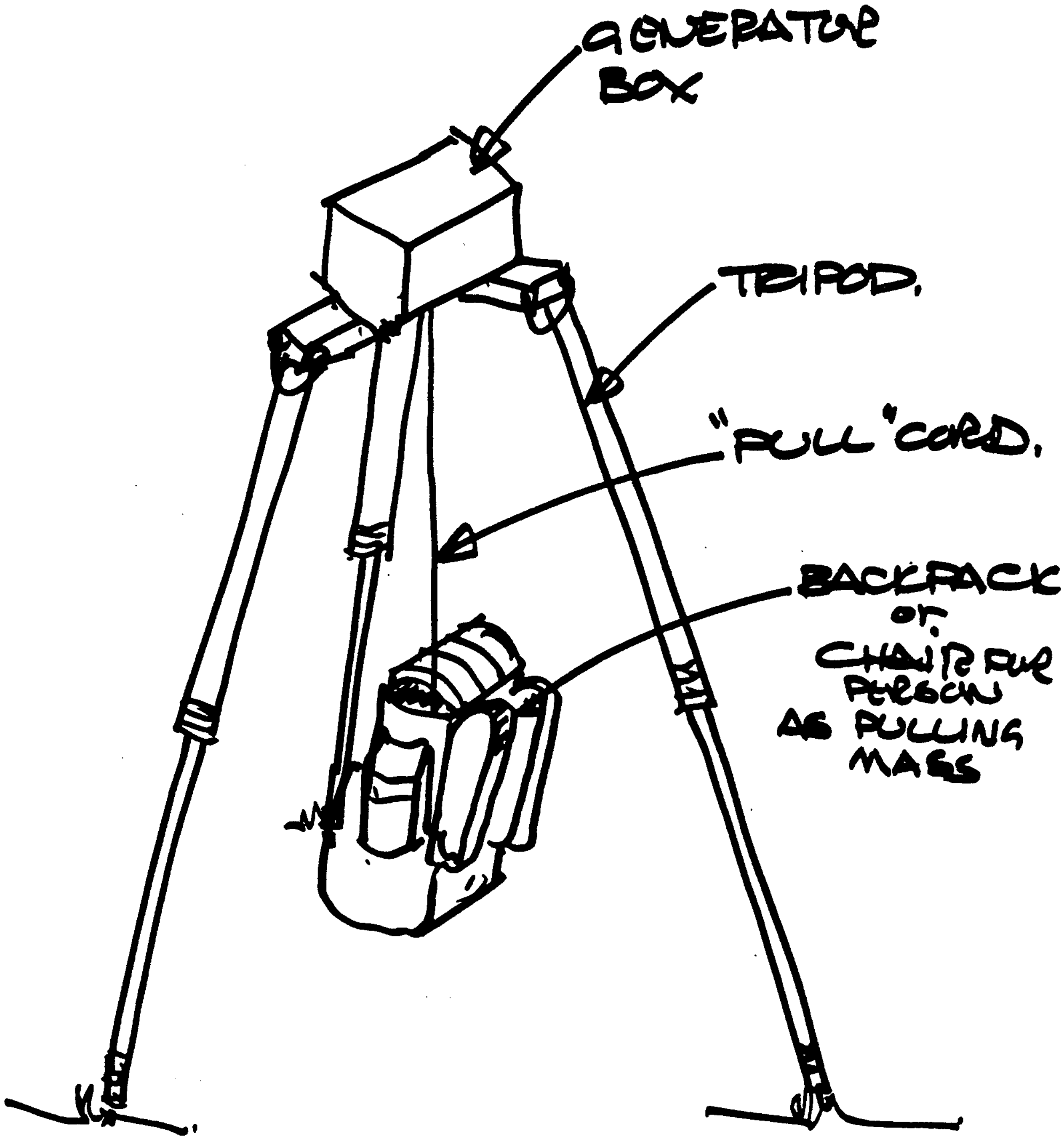
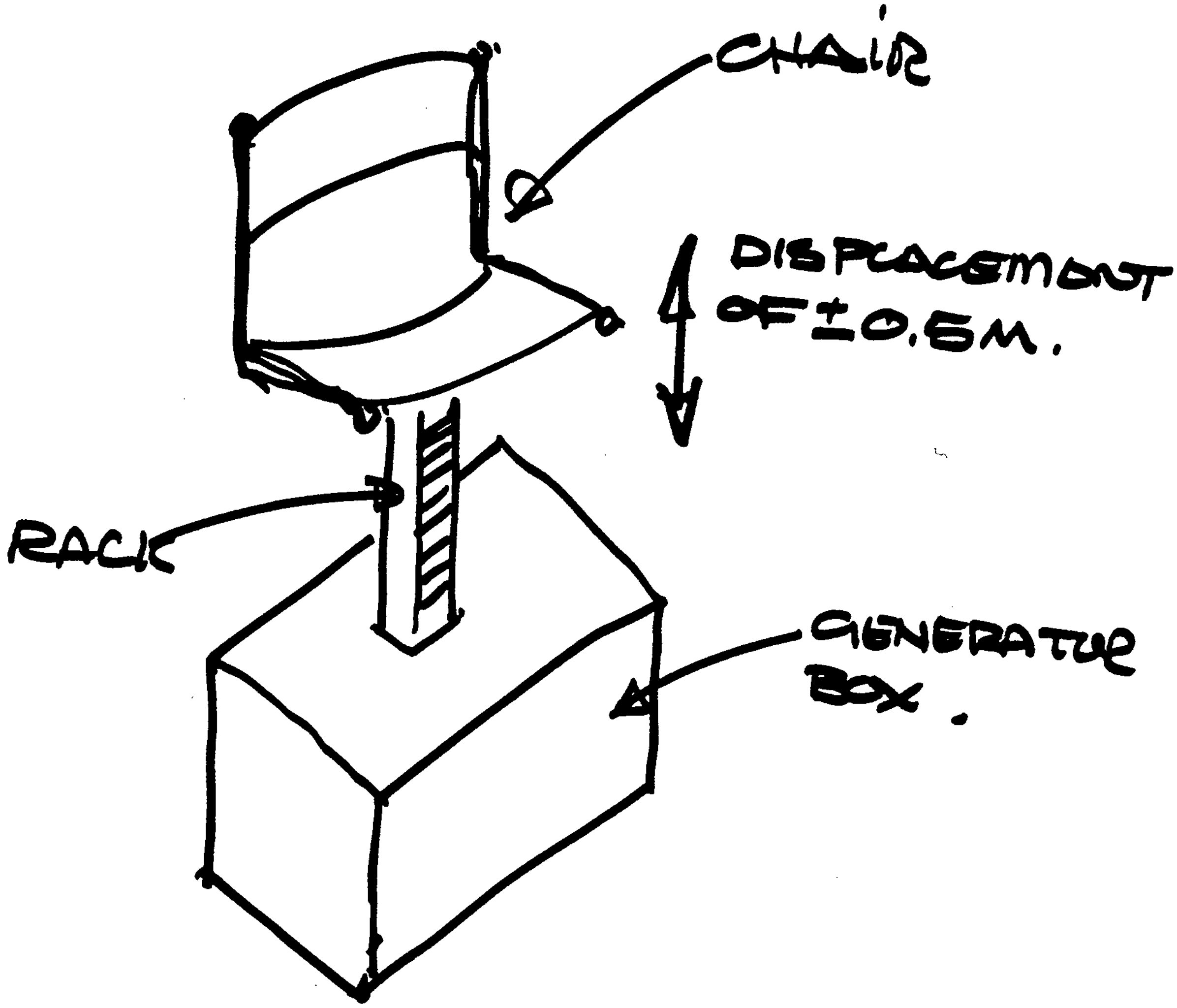
GENERATOR/
SPRING
STORAGE
MECHANISM
ATTACHED/INTEGRAL
WITH BOOT (MOUNTING POSITION TBD).

DISPLACEMENT OF HEEL OR
FLEXION OF BOOT IS RELAYED
TO SPRING TO WIND SPRING.
WHICH DRIVES GENERATOR.
MOTION IS CONVEYED TO
SPRING BY MECHANICAL
LINKAGE AND RATCHET.

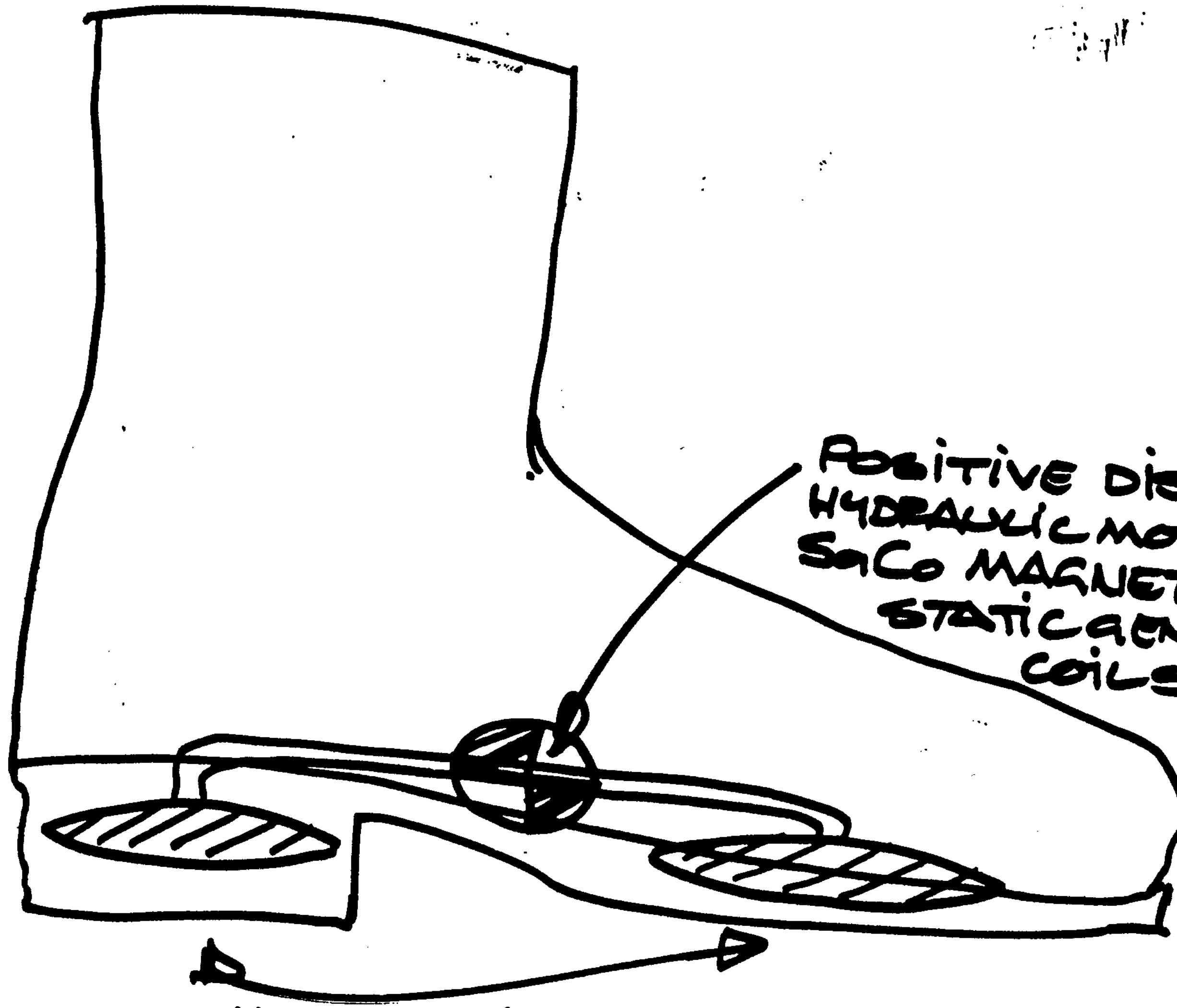
1) CONCEPT:



THIS CONCEPT MINIMISES FATIGUE OF CONTINUOUS HAND CRANK OF GENERATOR BOX.

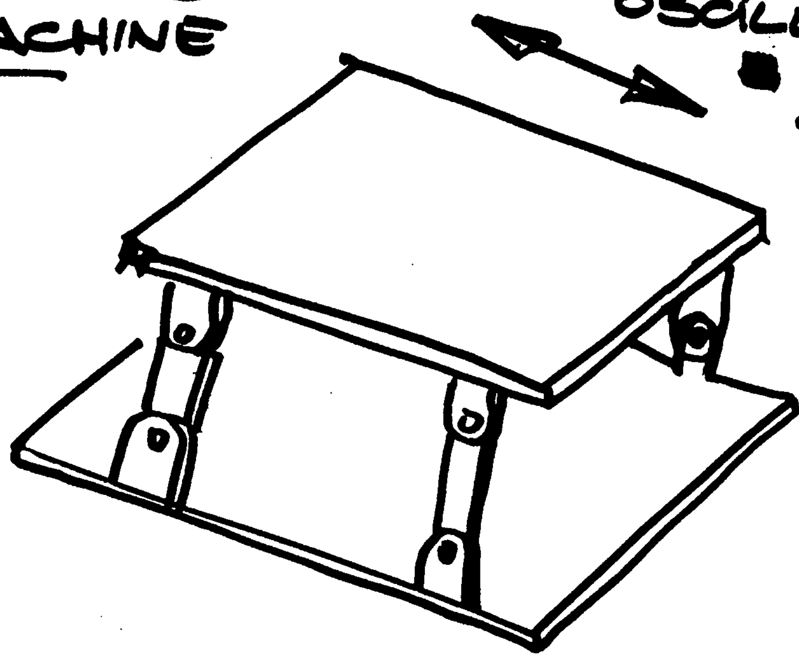


MASS OF PERSON DEPRESSES RACK, TURNING PINION. FOR DIRECT GENERATOR TURNING.


POSITIVE DISPLACEMENT
HYDRAULIC MOTOR WITH
SmCo MAGNETS ON ROTOR
STATIC GENERATOR
COILS.
HEELSTRIKE TO TOE TRANSFERS
FLUID THRU' POSITIVE DISPLACEMENT
MOTOR.

CONCEPT:

ROCKING CHAIR
ROWING MACHINE
?



FORWARD/BACKWARD OSCILLATION LINKED TO GENERATOR (THRU SPRING STORAGE DEVICE?).

PERSON SITS ON PLATFORM TO FACILITATE OSCILLATION.

WORKING GROUP 3 SUMMARY

RESEARCH

Research Area	State-of-Art	Developm't Potential	Risk	Priority
Human Body	Sports medicine Military Charaterization Performance Enhancement	Not done within the context of harvestng energy from the human body Excellent potential		High

RESEARCH

Research Area	State-of-Art	Developm't Potential	Risk	Priority
Mechanical to Electrical Electromagnetic (generators)	Well established in small motors which are inefficient when used as a generator. Few examples of small efficient gen.	Apply design rules for small motors to design generators. Excellent improvements possible.	Low	High
Mechanical to Electric Piezo-electro	Predominately used in actuators. New materials are being developed. Special applications where efficieny not an issue.	Research needed for new materials. Issues of matching/coupling. Development potential unclear.	High	Medium to High
Mechanical MEMS-Electric	Rapidly eloving in other fields. Mostly mechanical. Has not focussed on conversion to electricity. Major DOD/DARPA programs.	Development potential shoujld be high. MEM fabrication technicaes are well developed. Electrostatic generators.	Moderate	Medium

RESEARCH

Research Area	State-of-Art	Developm't Potential	Risk	Priority
Thermal to Electric Thermoelectrics	SOA well established in high T regime. Major DARPA/Navy Program for new materials operating near room temp.	Inherently low power low efficieny for low ΔT. Large area needed. (Pay off high)	High	Low
Chemical to Electric from waste	Bio fuel cells emerging. Digesters etc in large sizes mature. Not applied to human waste	High payoff from some military applications. Time constrants. Excellent potential	High	Medium to high

RESEARCH

Research Area	State-of-Art	Developm't Potential	Risk	Priority
Storage Flywheels	Established over a wide range of sizes Mature	Mature with low potential in general. Development potential for bearings	Low	Low
Springs	Established over a wide range of materials. Approximate 1j/gm storage system 0.5 j/gm	Mature with development for input and output mechanisms	Low/ medium	Low
Batteries	Well established rapidly evolving technology. Focus on high energy density.	Smart batteries. State of health. Temperature and environmental issues. Excellent	Low/ medium	High

RESEARCH

Research Area	State-of-Art	Developm't Potential	Risk	Priority
Storage Supercaps	Well developed in some devices. New materials are emerging prototypes on order of 20 j/gm 10kw/kg.	Need understanding of leakage mechanisms. Cell aging and balancing. Fabrication technique. Reliability. Excellent potential	Low	High
Distribution	Unclear piece/parts exist	Need architecture global architecture for solider. Excellent	Low/ High	High

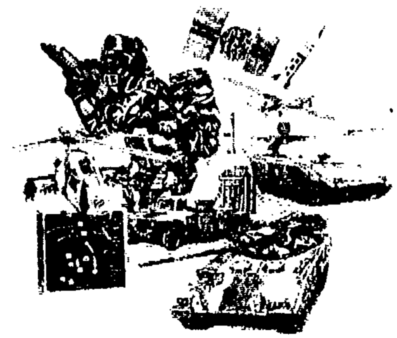
OVERVIEW SESSION 1

"SOLDIER SYSTEM IN 20 YEARS"

Mr. Robert O'Brien

Soldier Systems Command
Natick, MA 01760

Soldier Systems
The Path to Army After Next



Briefing to
Prospector IX Workshop:
Human Powered Systems

3 Novemebr 1997

Mr. Robert O'Brien
Warrior Systems Group
Soldier Systems Command

Soldier Systems Potential for AAN
Land Warrior Consolidated Program

Provides:

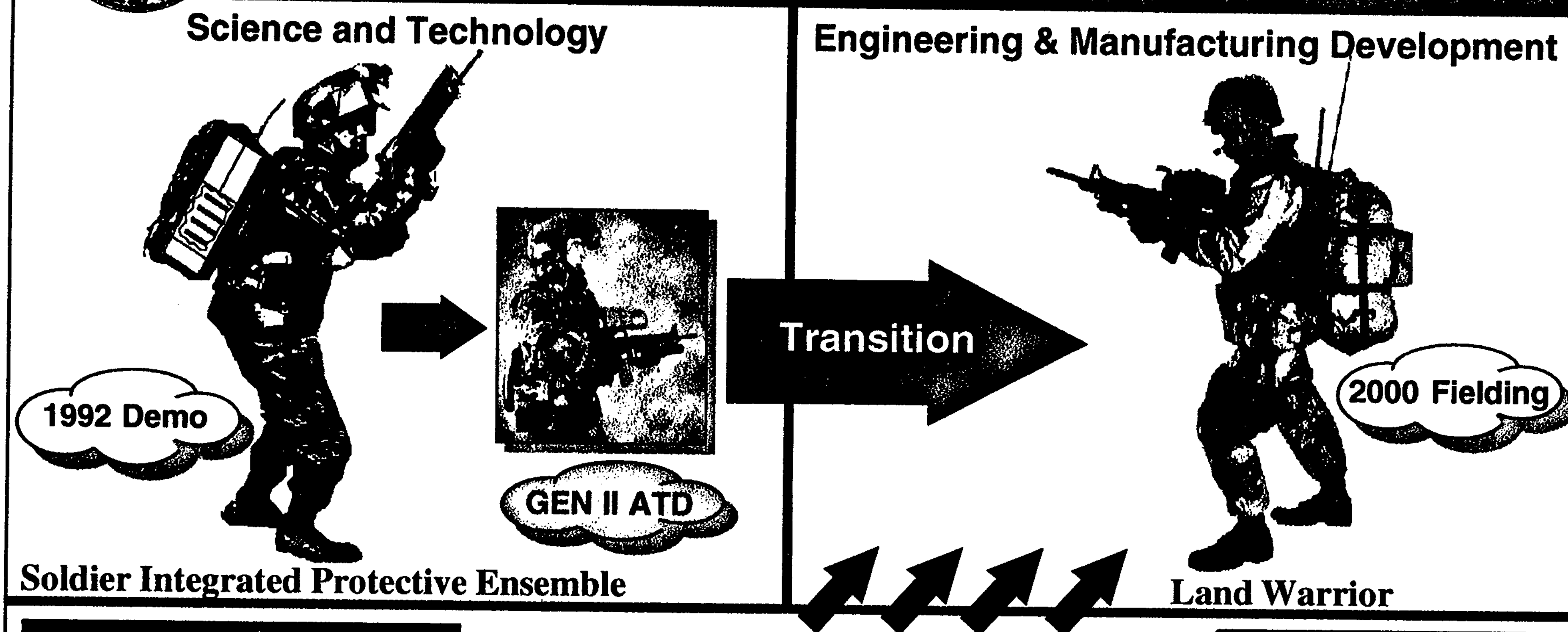
- Digitization for the Dismounted Warrior
- Situational Awareness
- Target Acquisition and Automated Handover
- Improved Protection
- Enhanced Vision Capabilities

Subsystems:

- Computer Radio
- Integrated Helmet Assembly
- Weapon (Includes sight)
- Protective Clothing and Individual Equipment
- Software

Modular Integrated Fighting System for the Dismounted Warrior

Soldier Systems Potential for AAN
Soldier Modernization



Force XXI Land Warrior

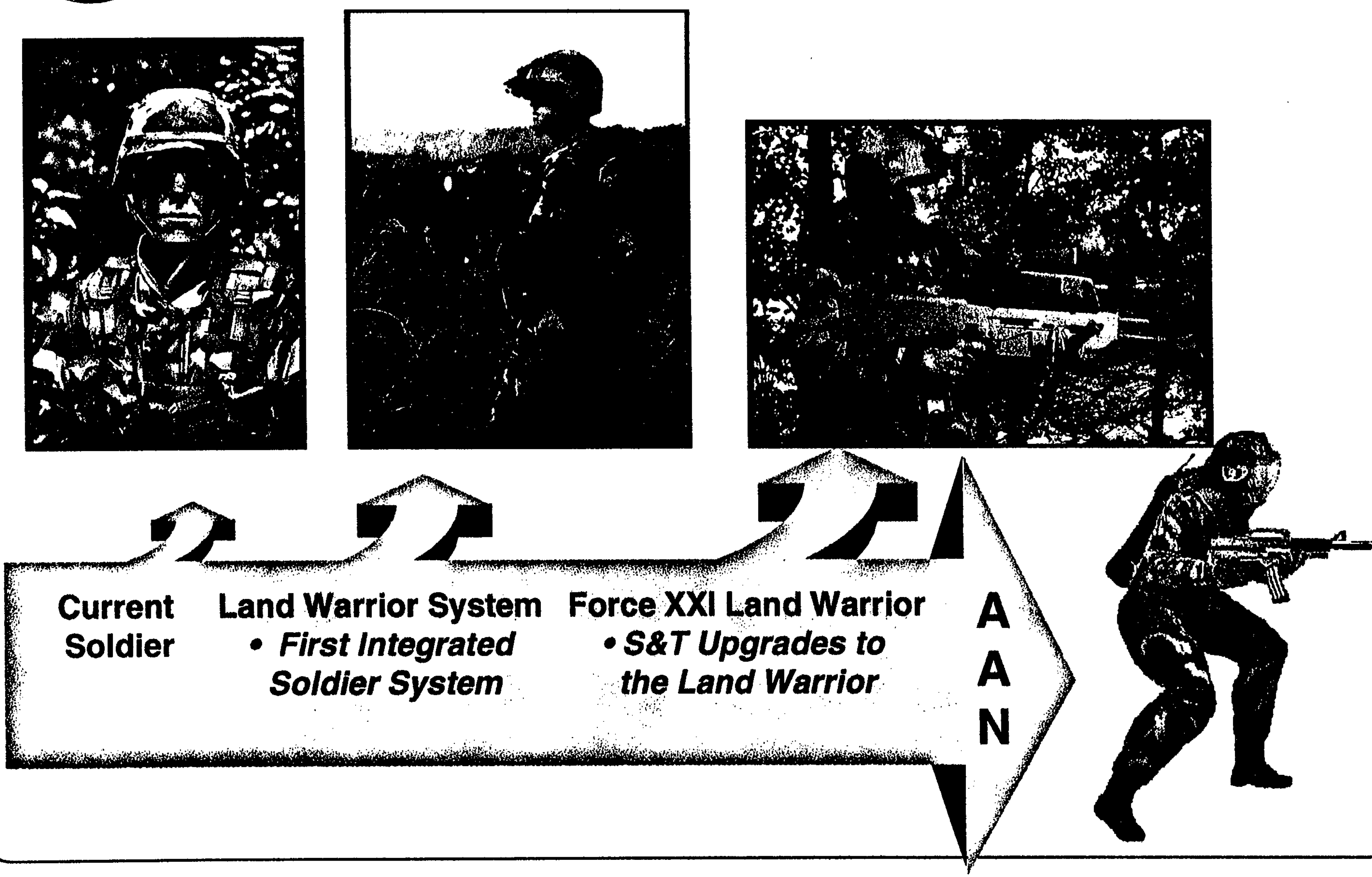
- Enhanced Range Soldier Radio
- Enhanced Weapon Interface
- Integrated Sight*
- Integrated Navigation
- System Voice Control
- Interface with Combat ID
- Head Orientation Sensor
- Helmet Mounted Display - Low Power Electronics
- Reduced Helmet Weight - Risk Reduction*

Provides Enhanced Capabilities

* Reduces weight

S&T Provides the Foundation for Revolutionary Upgrade for the Soldier

A Soldier System Path to Army After Next



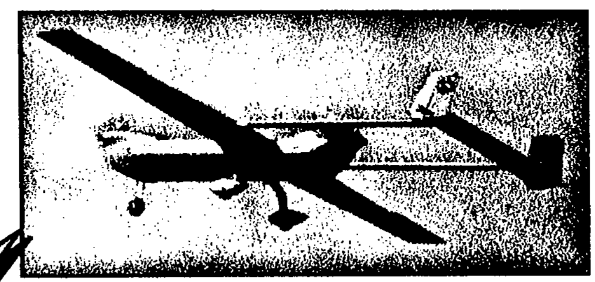
Target Acquisition

- Current Capability
  - M16A2 Rifle
  - Line of sight scopes out to 600 meters

- Land Warrior Capability
  - M16A2E4/M4E2 Modular Weapon Systems
  - Allows soldiers to acquire and hand over targets out to 1100 meters
  - S&T will add Objective Individual Combat Weapon which will provide 20mm exploding munitions capability to defeat targets in defilade
  - S&T capability out to 2500 meters

Future Technologies

- Army After Next Capability
  - Automatically acquires and hands over targets to appropriate supporting weapon in all conditions, day/night, and through obscurants
  - Selectable lethality
  - Self-guided personnel projectiles
  - Hands Free Weapon System
  - Target recognition, tracking



Dramatically Increased Soldier Lethality

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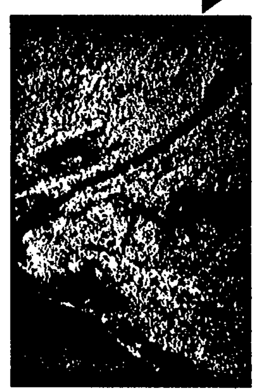
Situational Understanding

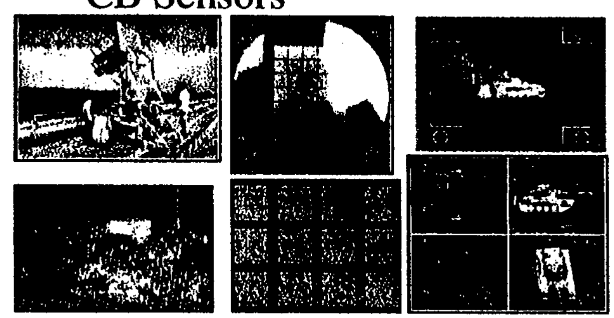
- Current Capability
  - Soldier vision, hand signals, word of mouth capabilities

- Land Warrior Capability
  - Linkage to digital battlefield, known enemy, friendly positions available and displayed on digital maps within heads-up display
  - Real time data updates available from higher echelons

Future Technologies

- Army After Next Capability
  - Complete full time link to all available battlefield assets, automatically selected for unit, position, and mission
  - Holographic Imaging/Decoys,
  - Complete sensor fusion (thermal, image intensifiers, geolocation, etc.)
  - Preposition sensor capabilities
  - Wide Band Mobile Internet, Manportable Mini-Base Stations
  - Counter Sniper
  - CB Sensors





Complete Sensor Fusion

Maneuver

- Current Capability
  - 75 pound fighting load, paper maps, compass, stand alone GPS unit (PLGR)

- Land Warrior Capability
  - 75 pound fighting load with advanced capabilities, digital maps linked to integrated GPS
  - Allows soldiers to move more accurately and quickly
  - S&T effort will integrate additional positioning capability when GPS not available

- Army After Next Capability
  - Dramatically reduce overall system weight with even more capability, ~ 50 lb fighting load
  - Automatically selects best route, predicts enemy movements and counter maneuvers
  - Dramatically increase movement rates with mechanical assist, or individual/group transporters
  - Exact airdrop insertion for troops/units
  - In Stride Mine Avoidance

Warrior Protection

- Current Capability
  - Protection from air burst munitions to head and torso, direct fire munitions to torso
  - Multiple layer/component approach to provide environmental/chemical protection
  - Visual, near IR countersuveilance

- Land Warrior Capability
  - Same capabilities at a slightly reduced weight
  - S&T will provide Combat ID functionality

Future Technologies

- Army After Next Capability
  - Fully integrated protection to reduce bulk, logistics, and weight, Spray-on Second Skin
  - Signature Control (Near/Mid/Far IR, Visual, Acoustic, Radar, Chameleon)
  - Protection from direct fire munitions to head and torso at a dramatically reduced weight
  - Advanced Physiological Monitoring (e.g., muscle response/fatigue, vital organ functions, etc.)
  - Identification of friendly, enemy or non-combatants

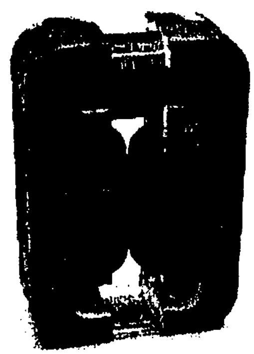
Superior Force Protection

Sustained Operations

<u>Power is Limiting Capability</u>

- Current Capability
  - 12-24 hours of sustained operations without re-supply (METT-T dependent)
- Land Warrior Capability
  - 12 hours of sustained operation without re-supply with four batteries (3 pounds) with enhanced capabilities

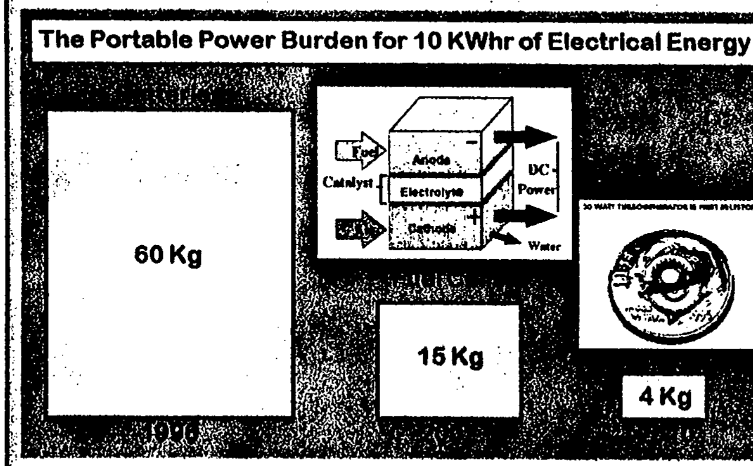
Future Technologies



Leap Ahead Capability in Manportable Power Sources

- Army After Next Capability
  - ~7 days of sustained operations without re-supply
  - New power sources (micro-turbines, etc.) provide revolutionary increase in manportable power capability
  - Renewable power sources

Compact Power Sources



Dismounted Warrior System
Power & Energy

- **Current LW system projections (FY00):**
  - Three BA-5847C/U LiSO2 Primary Batteries Required to operate for 12 hours
    - One on weapon, two man-worn
  - BA-5847C/U Data:
    - Weight = 11 ounces, Volume = 14.62 in^3
    - Capacity = 38 Watt Hours @ room temp.
    - Fused at 3 Amps
    - Between 12 and 16 Watts available depending on Battery "freshness"
    - Capacity at Low Temps are problem area
      - Losses near 50% at 0 degrees C
- **Typical 72 hour mission requires 18 BA-5847C/U Batteries per soldier**
  - 12.4 pounds & 263.25 in^3 of batteries

Dismounted Warrior System
Power & Energy

- **Largest Life Cycle Cost Driver for the Warrior System is <u>Batteries</u>**
- **What will help in the future?**
- **Technology**
  - Lower Power Electronics & Sensors
  - Improved Power Management Software and Techniques
  - Incremental Improvement in Battery Chemistries & Rechargeable technologies
  - New Power Sources
    - Fuel Cells
    - Human Powered Augmentation
    - Other "sleepers" (e.g., breakthrough in Solar, etc.)

Dismounted Warrior System
Power & Energy

- Adjustments to Tactics, Techniques and Procedures (TTPs)
  - Task Organize, Trade Offs on Basis of Issue
- Adding Capability to the Warrior System as Technology Advances makes the challenge more Significant
- Beginning in S&T & Continuing to Fielding Future Systems the Army Must Maintain Strong System Engineering and Discipline
  - Make Trade offs & Technology Improvements needed to bring the warfighter capability that is:
    - Light Weight, Affordable and Fightable

What Questions Need to Be Answered?

- ***How Will These Revolutionary Changes for the Warfighter Change the Way We Fight?***
- ***What Is the Right Mix of Technology To Maximize the Payoff?***
- ***How Do We Keep From Overwhelming the Dismounted Warfighter?***

"FUTURE REQUIREMENTS FOR THE DISMOUNTED SOLDIER"

Mr. Rudolf G. Buser

CECOM
Ft. Monmouth, NJ 07703-5201

Future Power Requirements for the Dismounted Soldier

Dr. Rudolf Buser

Communications - Electronics Command
Research, Development & Engineering Center
Fort Monmouth, New Jersey

FIELD CONCERNS

Battery Costs

Improved Performance

Disposal

Recharging

Weight

Unused Capacity

Maintenance

Proliferation

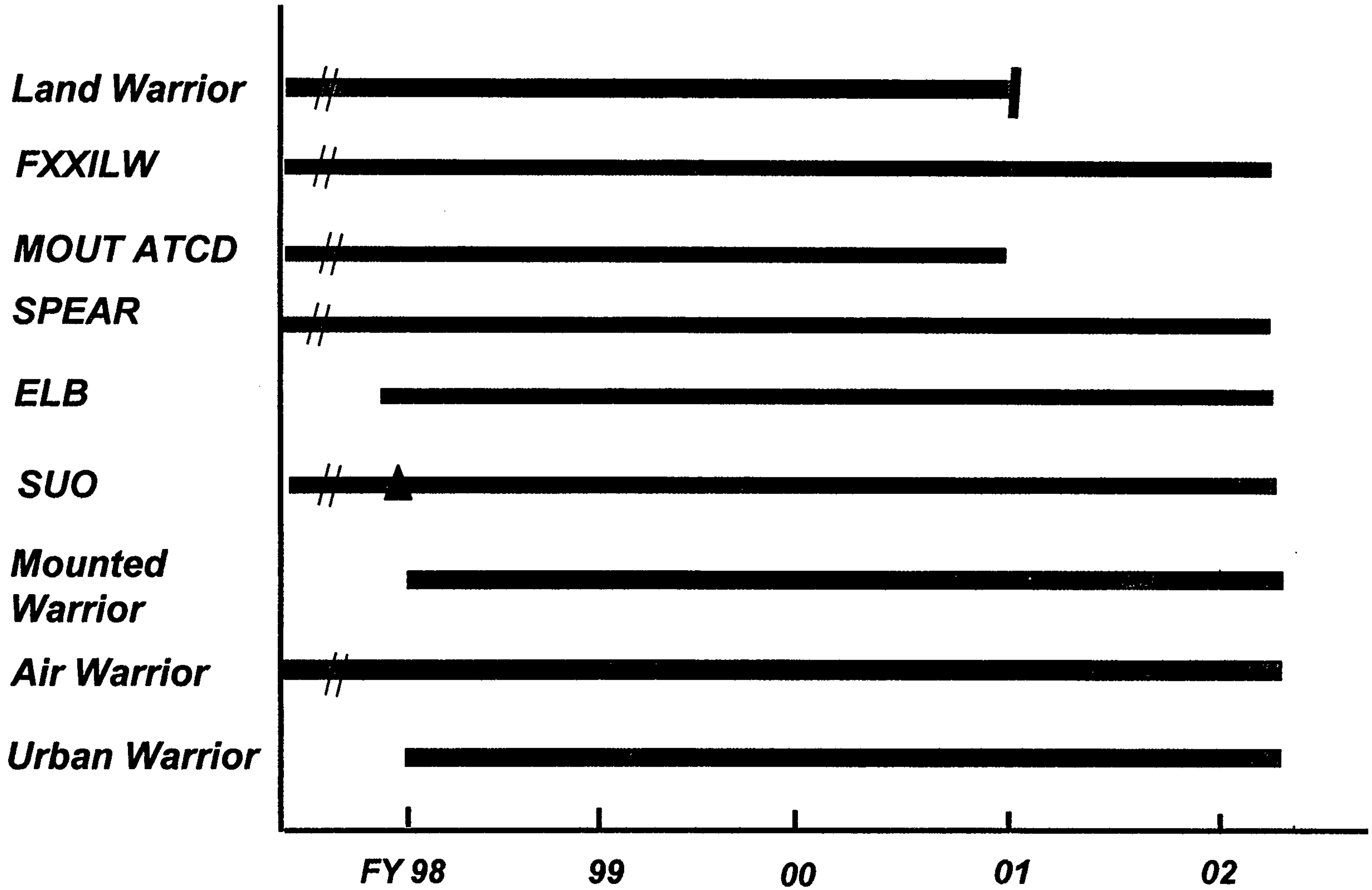
Soldier System Exit Criteria

Program	System Weight	Technical Approach	Energy Req.	Battery	Weight
Land Warrior	20 kg	Modular Weapon System Laser Range Finder Thermal Sight Weapon Combat ID Soldier Computer Soldier Radio GPS HUD	720 WHrs (72 Hrs) 8 W nominal	BB-2847 Li-Ion	24 lbs
SUO	<1 kg	Geolocation/Clocks Situational Awareness Sniper Detection Ground Sensor Tactical Comm.	450 WHrs (72 Hrs) 5 W nominal	BB-2247 Li-Ion BB-X847 Li-Poly	11 lbs 7 lbs
FXXILW	<20 kg	Enhanced Land Warrior Capabilities Wireless Weapon Interface Integrated Sight Voice Control Enhanced Radio Range Integrated Navigation	<450 WHrs (72 Hrs) 5 W nominal	BB-2847 Li-Ion BB-X847 Li-Poly	11 lbs 7 lbs

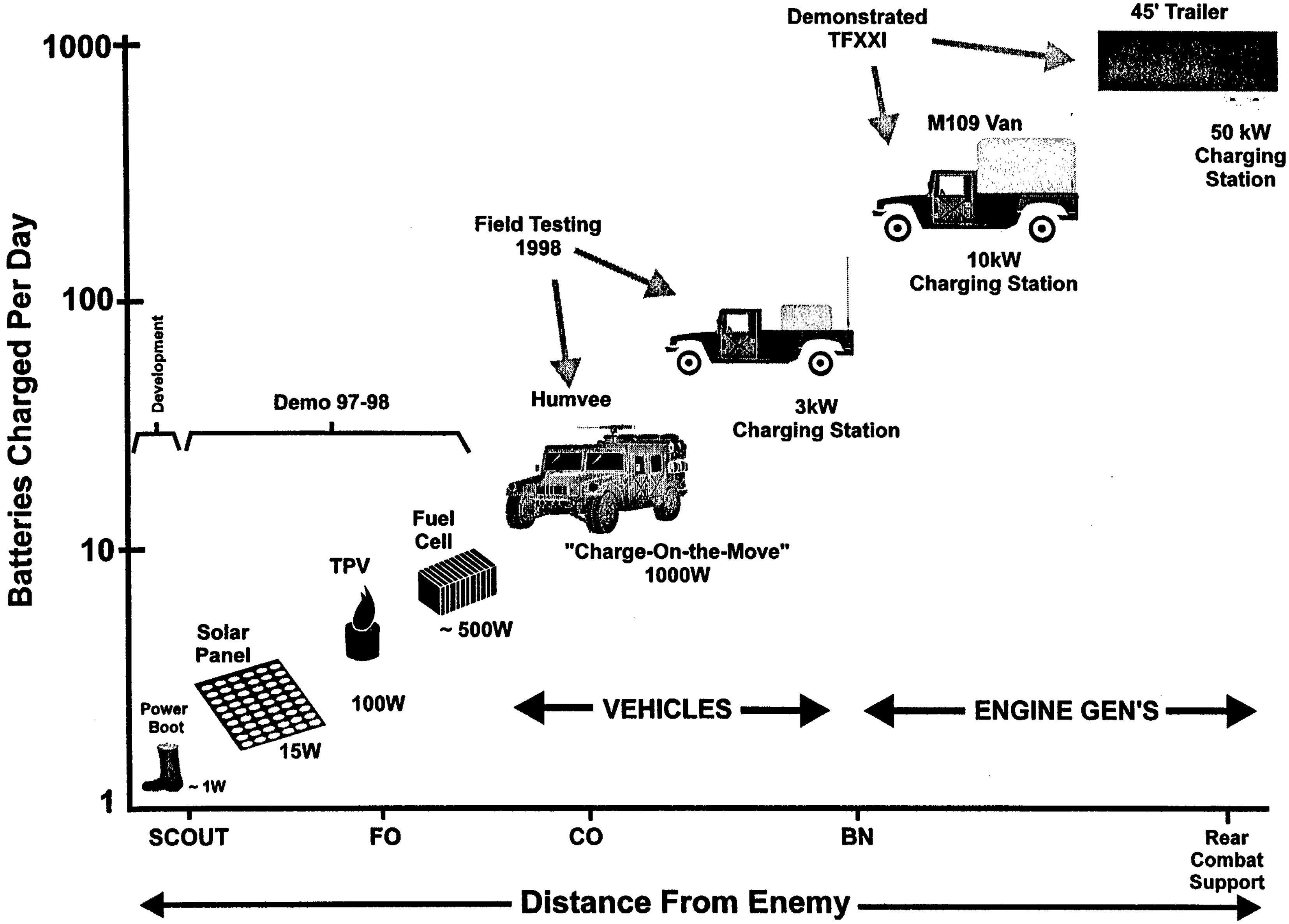
Soldier System Exit Criterias

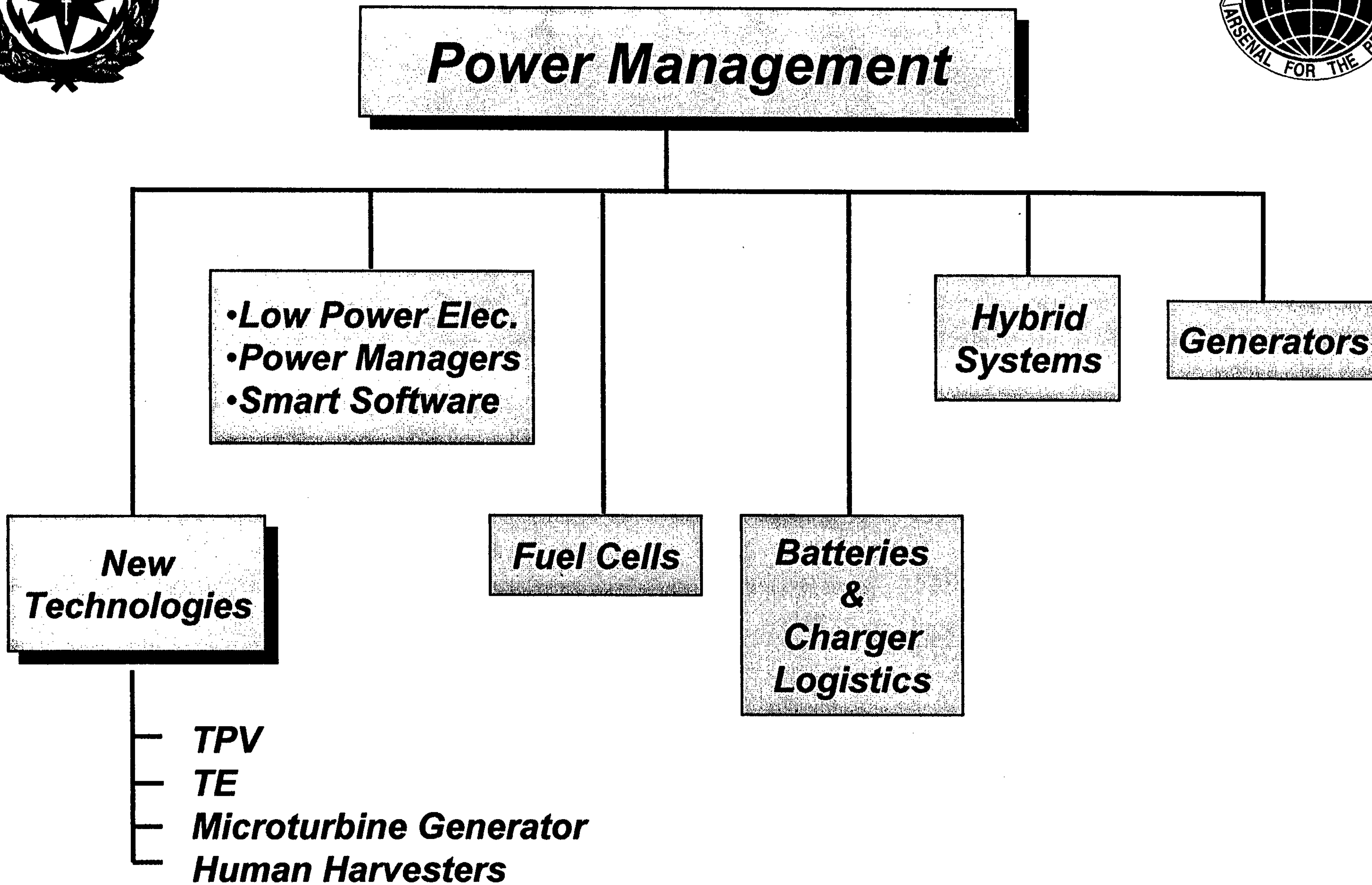
Program	System Weight	Technical Approach	Power Req.	Battery	Weight
Mounted Warrior	TBD	Leverage Existing Programs CVC Helmet Helmet Display Wireless Comm Uniform Ensemble	TBD	TBD	TBD
Urban Warrior	TBD	Leverage Existing Programs	TBD	TBD	TBD
ELB	TBD	Leverage Existing Programs COTS	TBD	TBD	TBD
MOUT ATCD	TBD	Leverage Existing Programs COTS, GOTS Integrated Protection Laser Protection Signature Control Combat ID Telemedicine	TBD	TBD	TBD

Current Programs

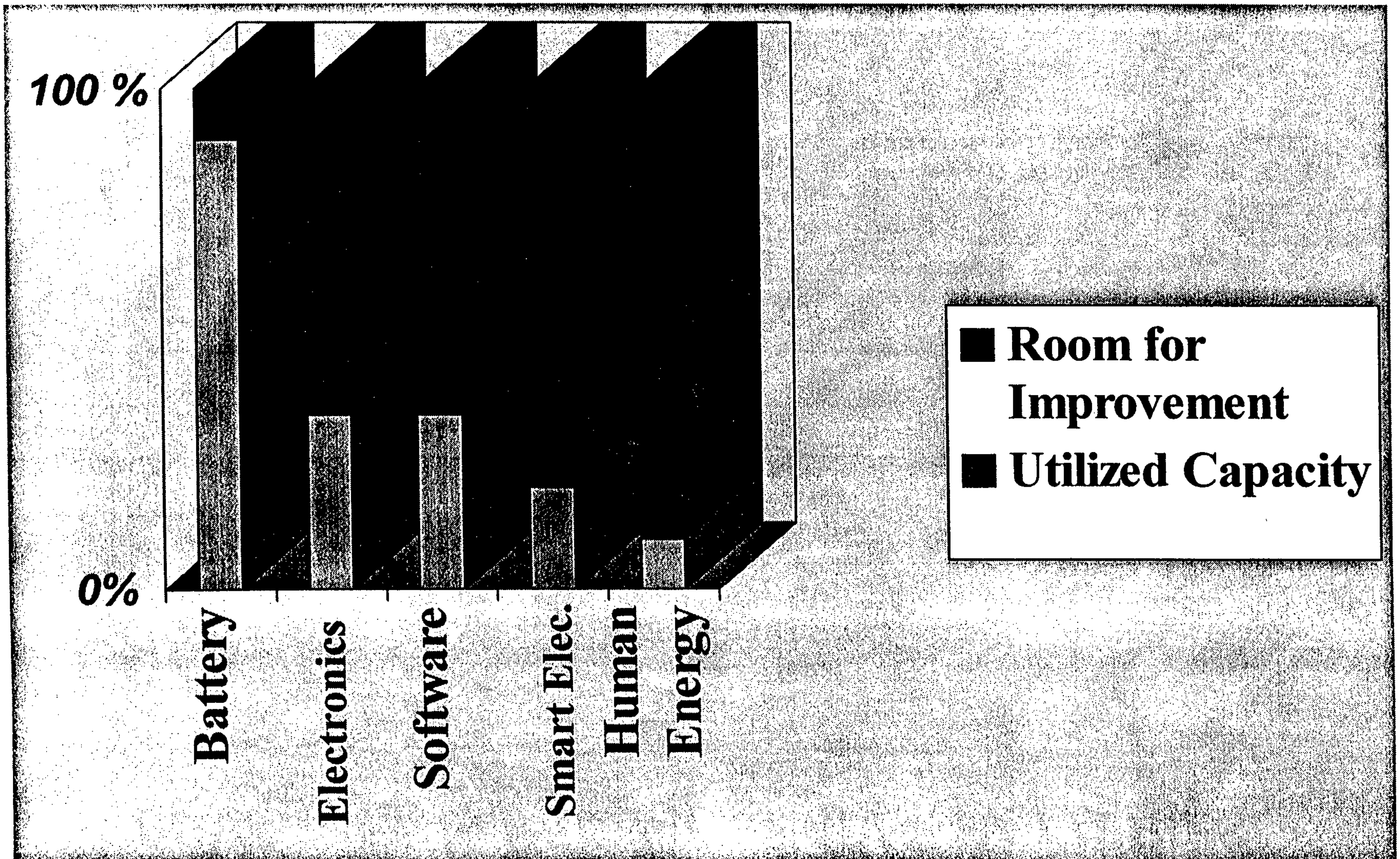


Present and Planned Battery Charging on the Battlefield

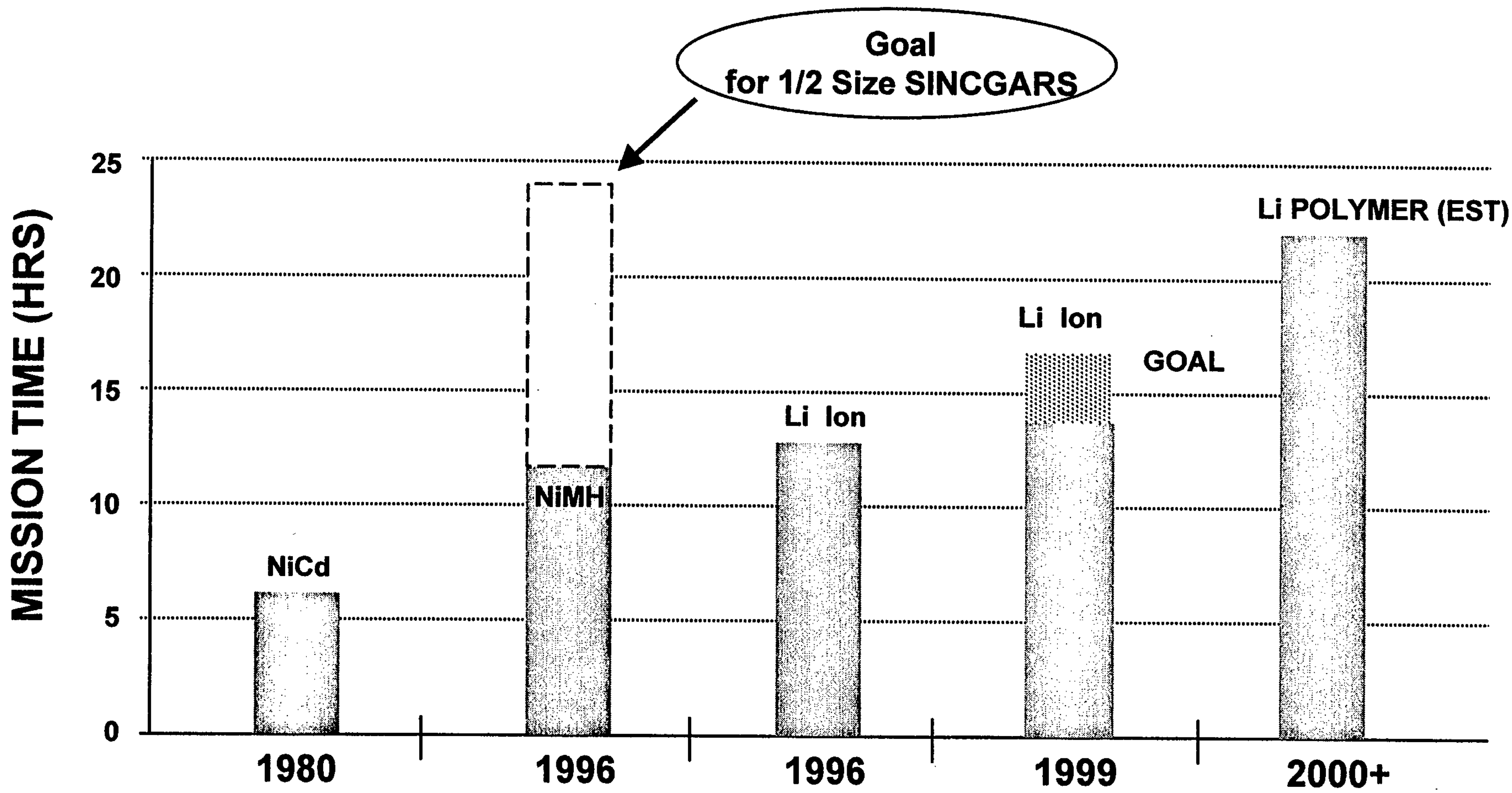



Power Management
New Technologies
TPV
TE
Microturbine Generator
Human Harvesters
•Low Power Elec.
•Power Managers
•Smart Software
Fuel Cells
Batteries & Charger Logistics
Hybrid Systems
Generators

Power Improvements



ADVANCES IN RECHARGEABLE BATTERIES

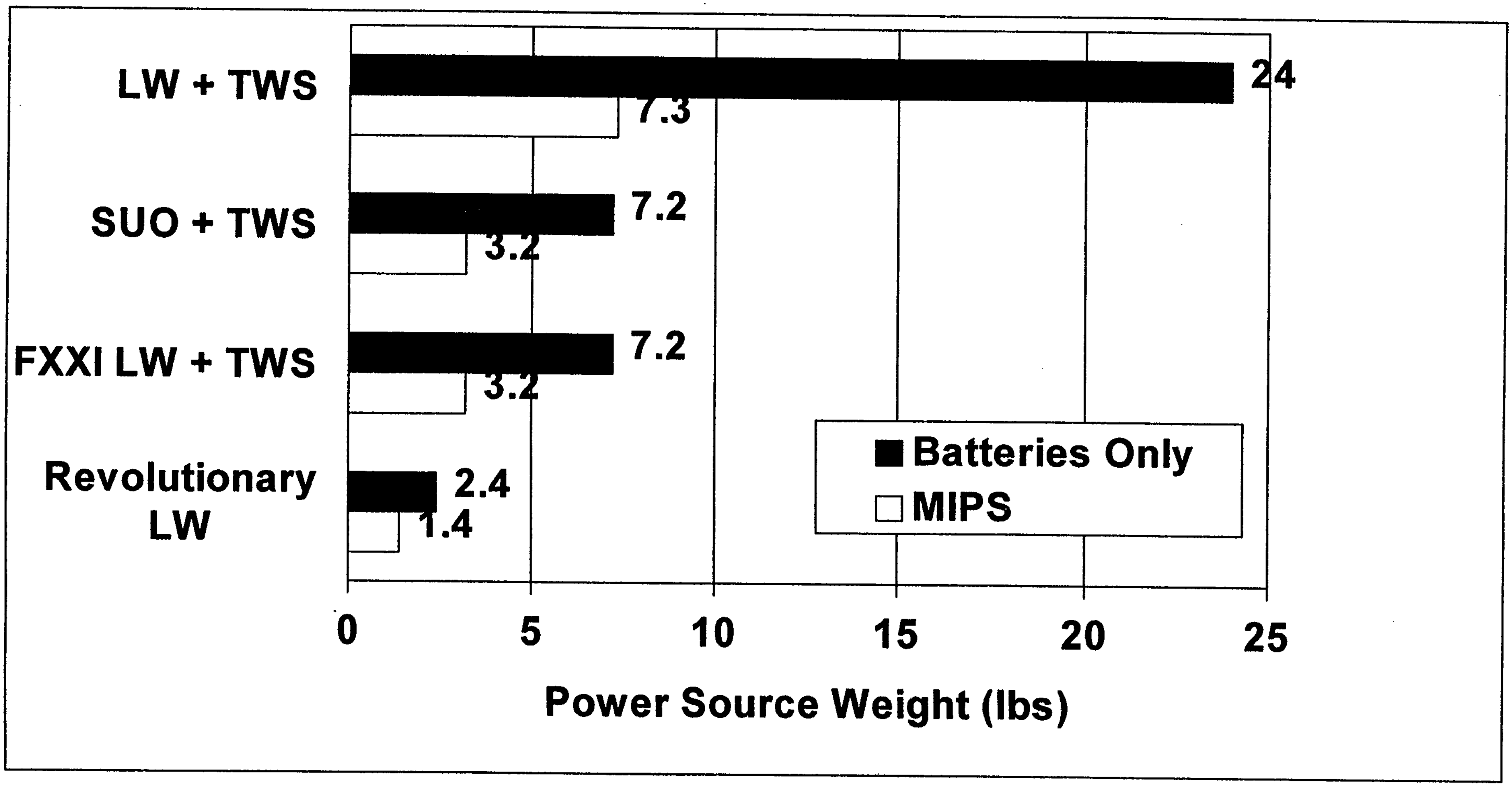


DATA BASED ON USE IN THE CURRENT SINCGARS RADIO

Meeting the Power Needs

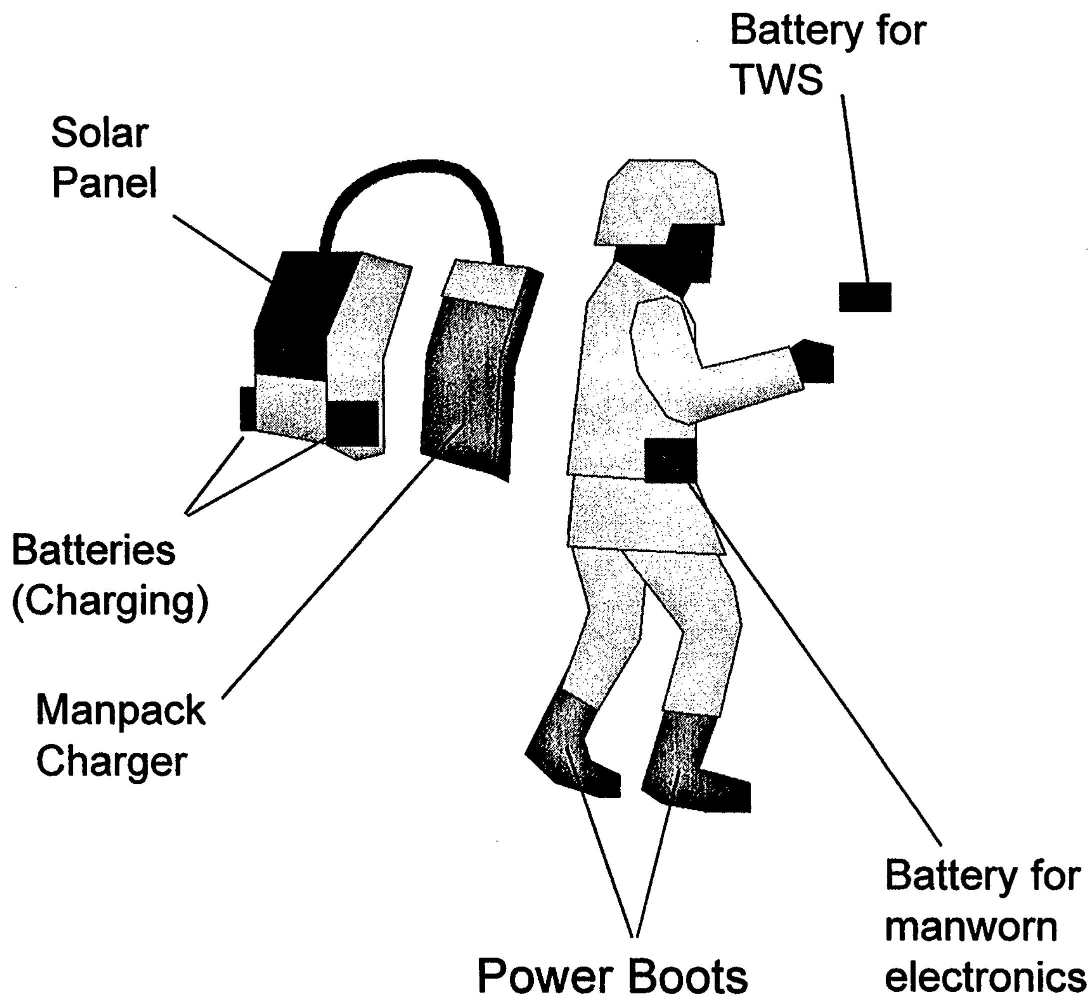
System	Nominal Power	Total Energy	Power Srce	Battery Wt
Land Warrior + TWS	8 Watts for 72 hours 6 Watts for 24 hours	720 Watt-hours	BB-2847/U Li-Ion	24 lbs
SUO + TWS OR FXXILW + TWS	5 Watts for 72 hours 3 Watts for 24 hours	432 Watt-hours	Li-Ion	11 lbs
SUO + TWS OR FXXILW + TWS	5 Watts for 72 hours 3 Watts for 24 hours	432 Watt-hours	Li-Polymer	7.2 lbs
Revolutionary LW + TWS	1 Watts for 72 hours 3 Watts for 24 hours	144 Watt-hours	Li-Polymer	2.4 lbs

Batteries Only Versus MIPS Approach for Future Power



MODULAR INTEGRATED POWER SYSTEM CONCEPT

- Integrated Manportable Charger/Battery System
- Battery recharged in 2 to 3 hours
- Battery operate equipments for 4 to 5 hours
- Charger refueled every 3 or 7 days
- Power boot and Solar Panel extends life of charger fuel



Conclusions

- ✱*Effective Power Management Provides Key to Soldier Platform Optimization*
- ✱*Interim Expectations:*
  - ✱*Battery Improvements*
  - ✱*Evolution of Fuel Cell / Battery Hybrids*
  - ✱*Introduction of Human Energy Harvesting*
  - ✱*Significant Impact on Power Consumption by Electronics, Smart Electronics, and Smart Software*
- ✱*Appetite involving increased power consumption must be considered*

"POWER FOR THE DISMOUNTED SOLDIER - A SUMMARY OF THE NRC STUDY"

Dr. M. Frank Rose

Space Power Institute
Auburn University, AL 36849

Prospector IX - Human Powered Systems Workshop

"A Brief Summary of the NRC Study of Power for the Dismounted Soldier"

M. Frank Rose, Director
Space Power Institute
231 Leach Science Center
Auburn University
Auburn, AL

Desert Storm

- Army shipped 2.2 million tons dry
- [redacted] total was ammo, mainly arty
- Army returned 1.6 million tons dry
- Not clear what was fired at enemy
- USAF delivered 70,000 tons of ordnance; 40 tons of fuel per ton delivered

Our Vision: in 20 Years.....

- **Early Entry Forces 33% of current manning**
  "Depopulate the zone of vulnerability"
- **Firepower 100% that of present force**
  "Situational understanding, precision fires..."
- **Teeth-to-tail ratio (in-theater) > 1.0**
  "Less vulnerability to asymmetric counters..."
- **Logistics just-in-time *vice* just-in-case**
  "Total asset visibility, precision delivery..."
- **Maintenance by need *vice* schedule**
  "Detect, remove, replace, as tele-coached..."
- **Acquisition driven by the engine of commerce**
  "Market oriented—like business..."

CHANGES IN THE ART OF WAR FOLLOW TECHNOLOGY DRIVEN CYCLES

2nd Wave
Industrial Age

Third Wave
Information Age

1865 — 1917 — 1961 — 1991 — 2010

Mental — Physical

Defense		Offensive		Defense		Offensive			
Speed	Killing Zone	Speed	Killing Zone	Speed	Killing Zone	Speed	Killing Zone	Speed	Killing Zone
2.5 km/hr	1.0 km	20 km/hr	15 km	30 km/hr	250 km	40 km/hr	?	200 km/hr	?

American Civil War

Gulf War

War in 2020

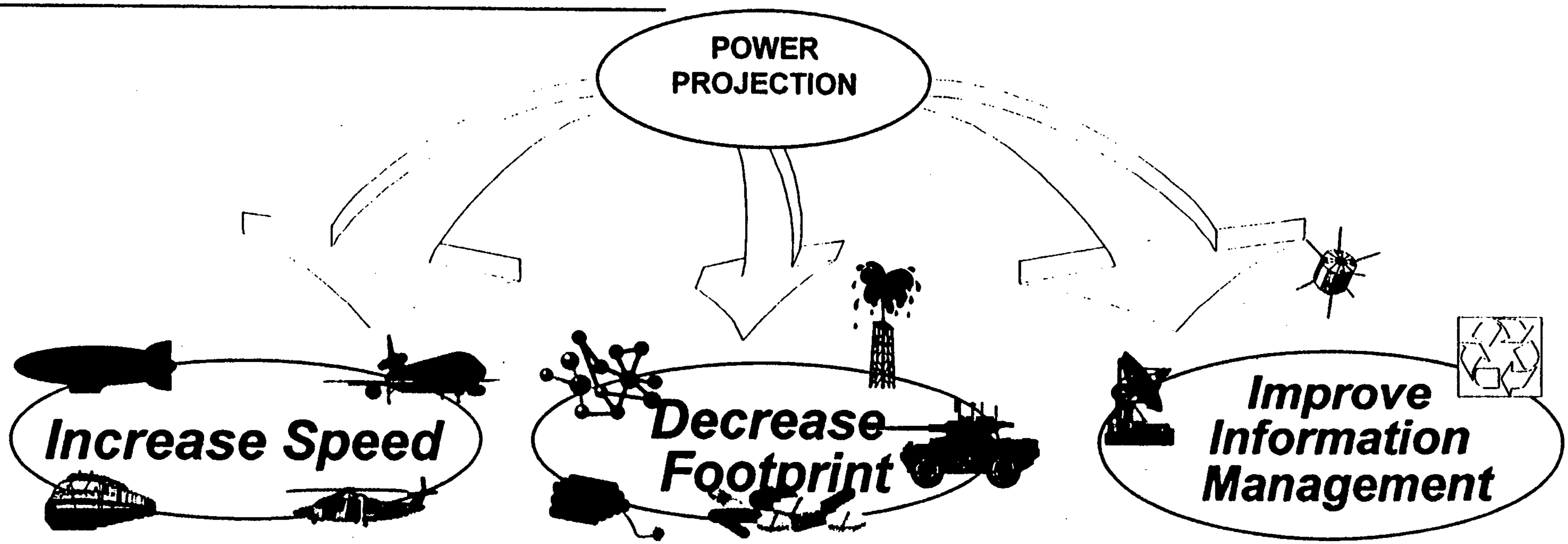
- Firepower Dominance
- Forces tied to Railhead
- Exhaustion through Attrition
- Symmetric Forces

- Maneuver Dominance
- Motorization, Wireless, Airpower
- Strike COG
- Asymmetric Forces

- Precision Firepower Dominance
- Early Warning, Tracking
- Attack to Operational Depth
- Symmetric Forces

- Information Enables Precision Maneuver
- Platforms Accelerate Speed
- Global Maneuver
- Asymmetric Forces

21st Century Power Projection



- High Speed Ships
- Next Generation Strategic Airlift
- Self-Deployable Tactical Multi-Role Aircraft
- Super Efficient Intermodalism
- High Speed Land Movement

- Lightweight Composite Materials
- Alternative Munitions
- Condensed Rations
- Alternative Power
- Super Efficient Engines

- Full Dimensional Awareness
- Infosphere Databases
- Total Process Simulations
- Transportation Based Distribution

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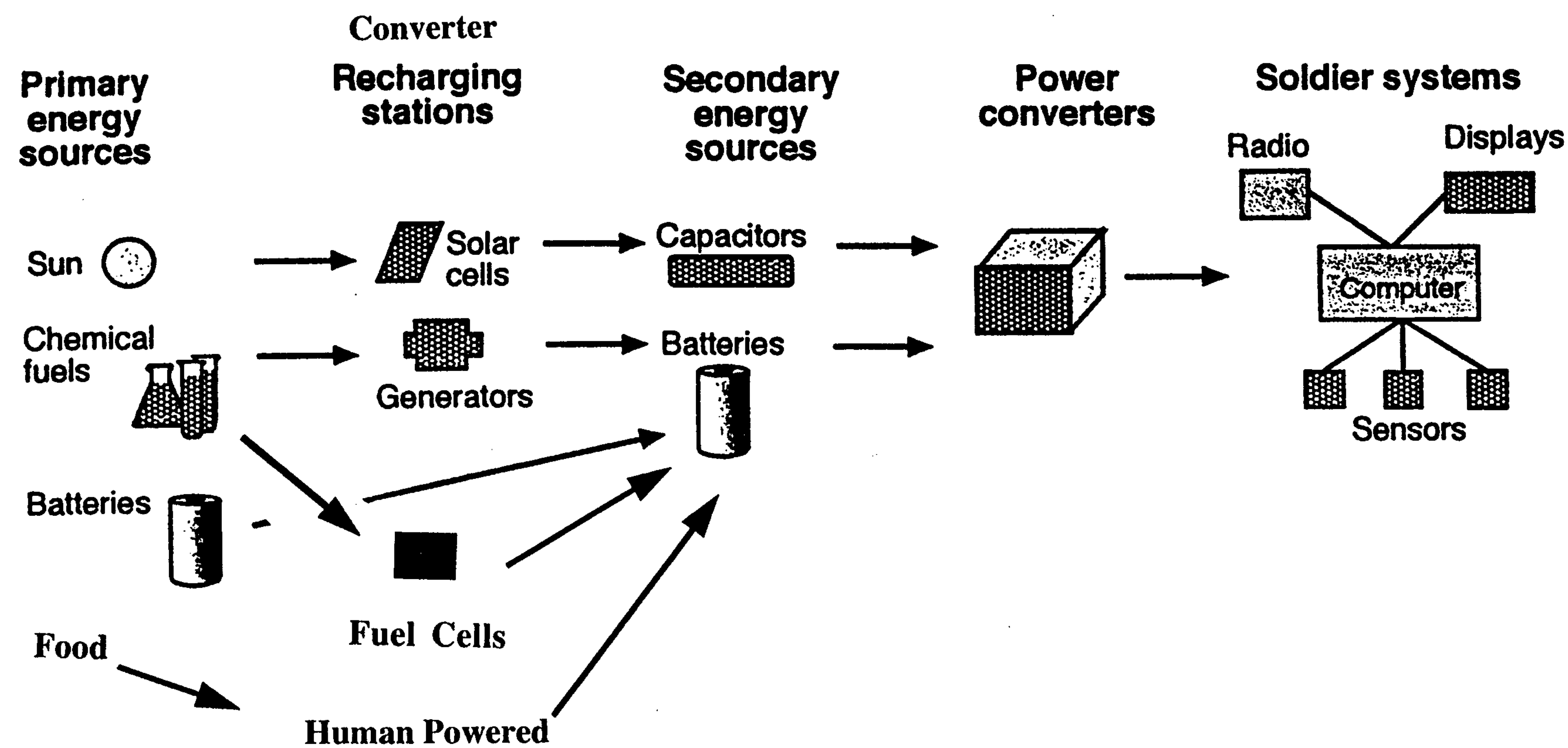

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Technology Summary of Energy Systems

Power System	State of the Art	Potential for Improvement	Key Issues	Scaling Laws	Impact on Dismount Soldier	Hostile Signature	Suppression Potential	Fuel Required	Autonomy Time
Primary Battery	Mature	Moderate	Energy density Safety Power density Environmental impact	Known	Longer mission Less weight Disposability	Minimal	Excellent	None	Hours/days
Secondary Battery	Mature	Moderate	Energy density Cycle life Power density	Known	New capability Cost savings Less weight	Minimal	Excellent	None	Hours
Thermophoto-voltaic	Emerging	Excellent	Requires cooling Efficiency Lifetime Ruggedization	Uncertain	New capability Cost savings Longer mission	Thermal	Moderate	Multifuel	Days/weeks
Fuel Cells (Hydrogen)	Exploratory development	Excellent	Fuel Water management Safety	Known	New capability Less weight Cost savings	Thermal	Excellent	Hydrogen	Days/weeks
Fuel Cells (Methanol)	Emerging	Excellent	Fuel and fuel crossover Catalyst	Uncertain	New capability Cost savings Less weight	Thermal	Excellent	Methanol	Days/weeks
Alkali Metal Thermal to Electrical Converters	Emerging	Excellent	Liquid metal Membranes Pumps/wicks Ruggedization	Uncertain	New capability Less weight Cost Savings	Thermal	Moderate	Multifuel	Days/weeks
Nuclear Isotope	Limited	Excellent	Safety Environmental impact Cost Public acceptance	Known	New capability Autonomy	Thermal Nuclear	Moderate	Special	Month/years
Internal Combustion	Some versions mature	Moderate to excellent	Fuels Vibration Life	Uncertain	Cost savings Less weight	Thermal Acoustic	Moderate	Multifuel (Some special)	Days/weeks
Microturbine	Emerging	Excellent	Safety	Uncertain	New capability	Acoustic	Difficult	Special	Days/weeks
Thermoelectric	Some versions mature	Moderate to excellent	Efficiency Materials Coupling	Known	New capability Less weight	Thermal	Moderate	Multifuel	Days/weeks
Human Powered	Nonexistent	Excellent	Conversion mechanisms	Unknown	New capability Cost saving Autonomy	Minimal	Excellent	Food	Weeks

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Activity	Power (W)
Sleeping	81
Standing at ease	128
Walking	163
Walking briskly	407
Long-distance running	1048
Sprinting	1630

Power Levels associated with Human Activity

Possible Harvestable Sources

Source	Maximum Power Available (W)	Estimated Conversion Efficiency
Body heat	116	~3% (assuming total capture)
Breath	1.0	40%(based on turbine efficiency)
Blood pressure	0.9	about 2%
Upper limb motion	24–60	< 3%
Walking (heel strike)	67	piezoelectric converter ~7% generator ~50%

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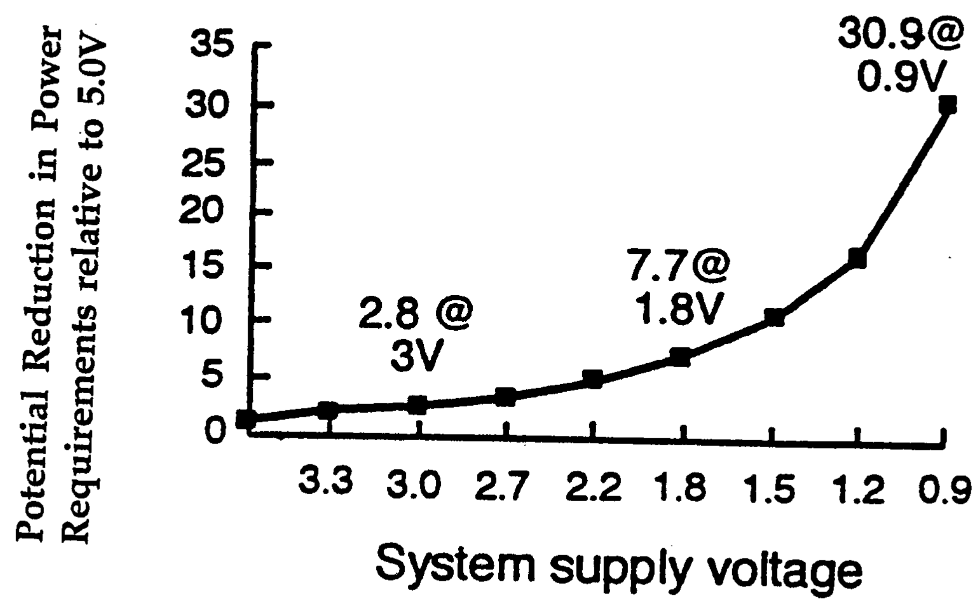
$$P = A \cdot C \cdot f \cdot V^2 + A \cdot I_{sw} \cdot V + A \cdot I_{leak} \cdot V$$

where

$A =$ percentage activity factor
$C =$ total chip capacitance (Farads)
$V =$ total voltage swing, usually near the power supply voltage (Volts)
$f =$ chip clock frequency (Hz)
$I_{sw} =$ short circuit switching current (Amps), current when both PMOS (p-type metal-oxide semiconductor) and NMOS (n-type metal-oxide semiconductor) are on simultaneously during a logic change
$I_{leak} =$ leakage current (Amps) from substrate injection and subthreshold effects

Silicon Power Reduction Best Known Methods

- Low power design best known methods
  - Circuit, logic, microarchitecture
- Advanced process and voltage scaling
  - 3.3V ➡ 1.8V
  - 0.5μm ➡ 0.25μm



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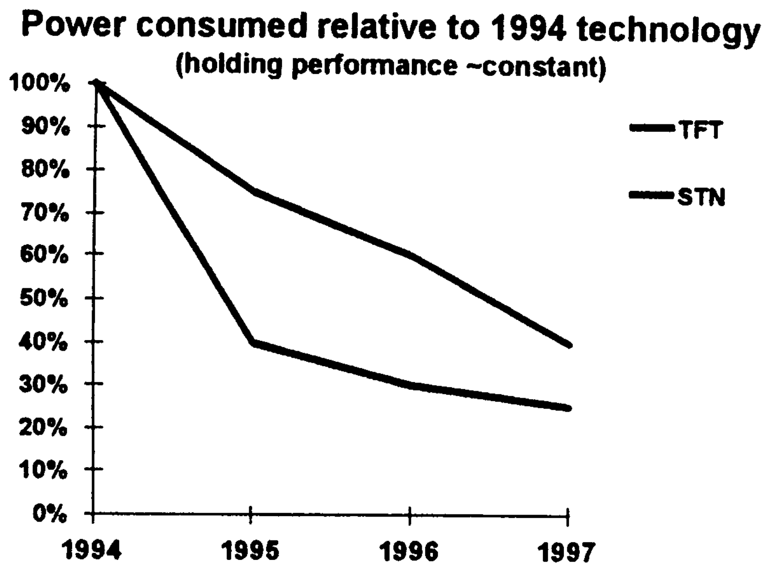
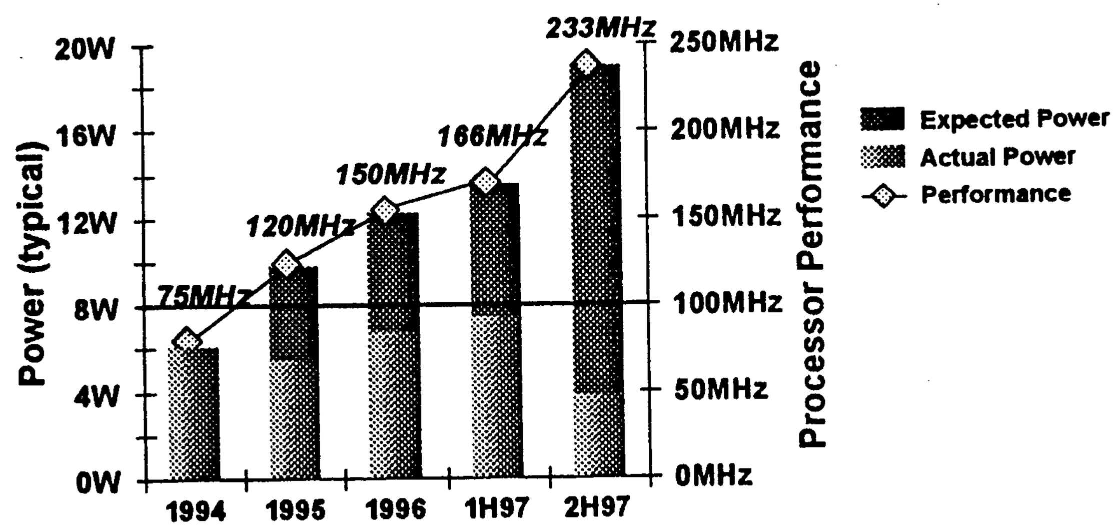


Displays



Processors

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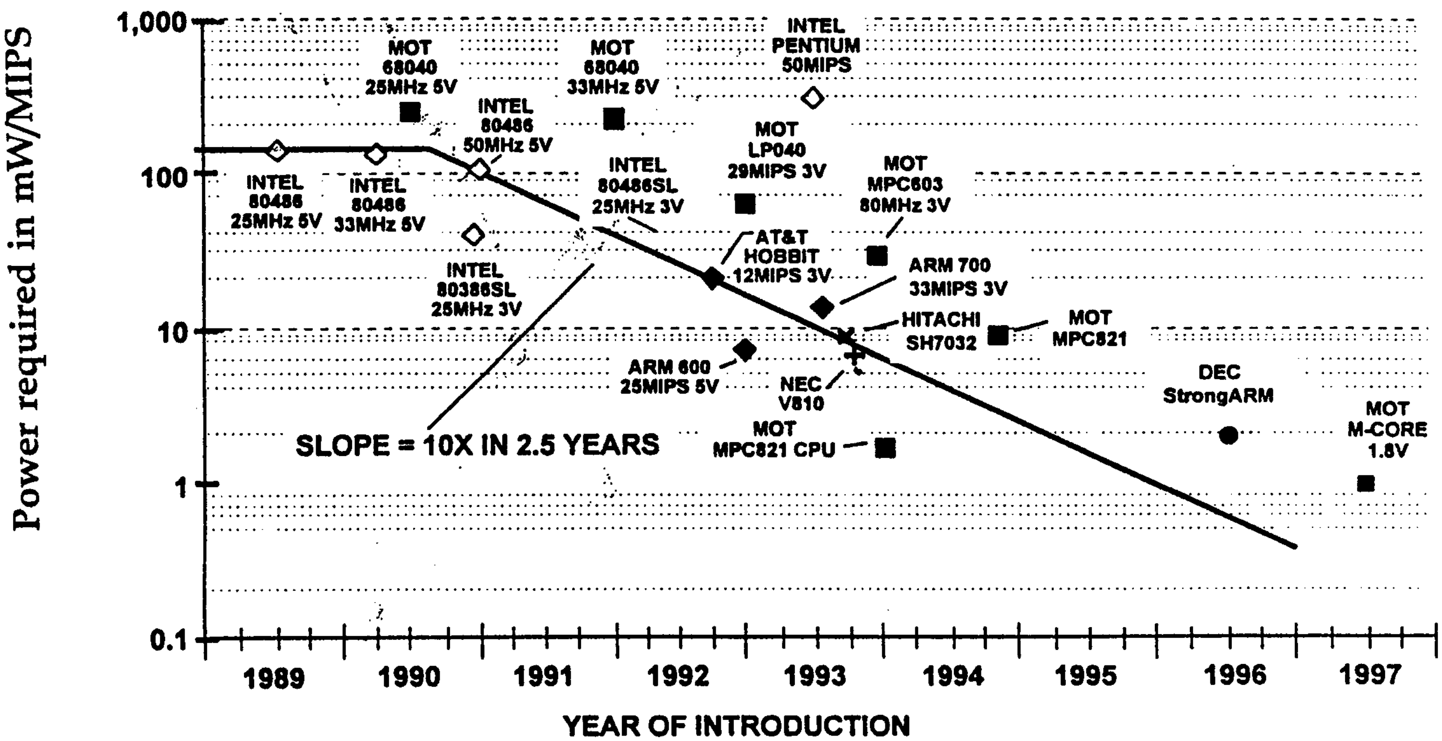
SPEED-POWER CHARACTERISTICS OF MICROPROCESSORS vs. TIME



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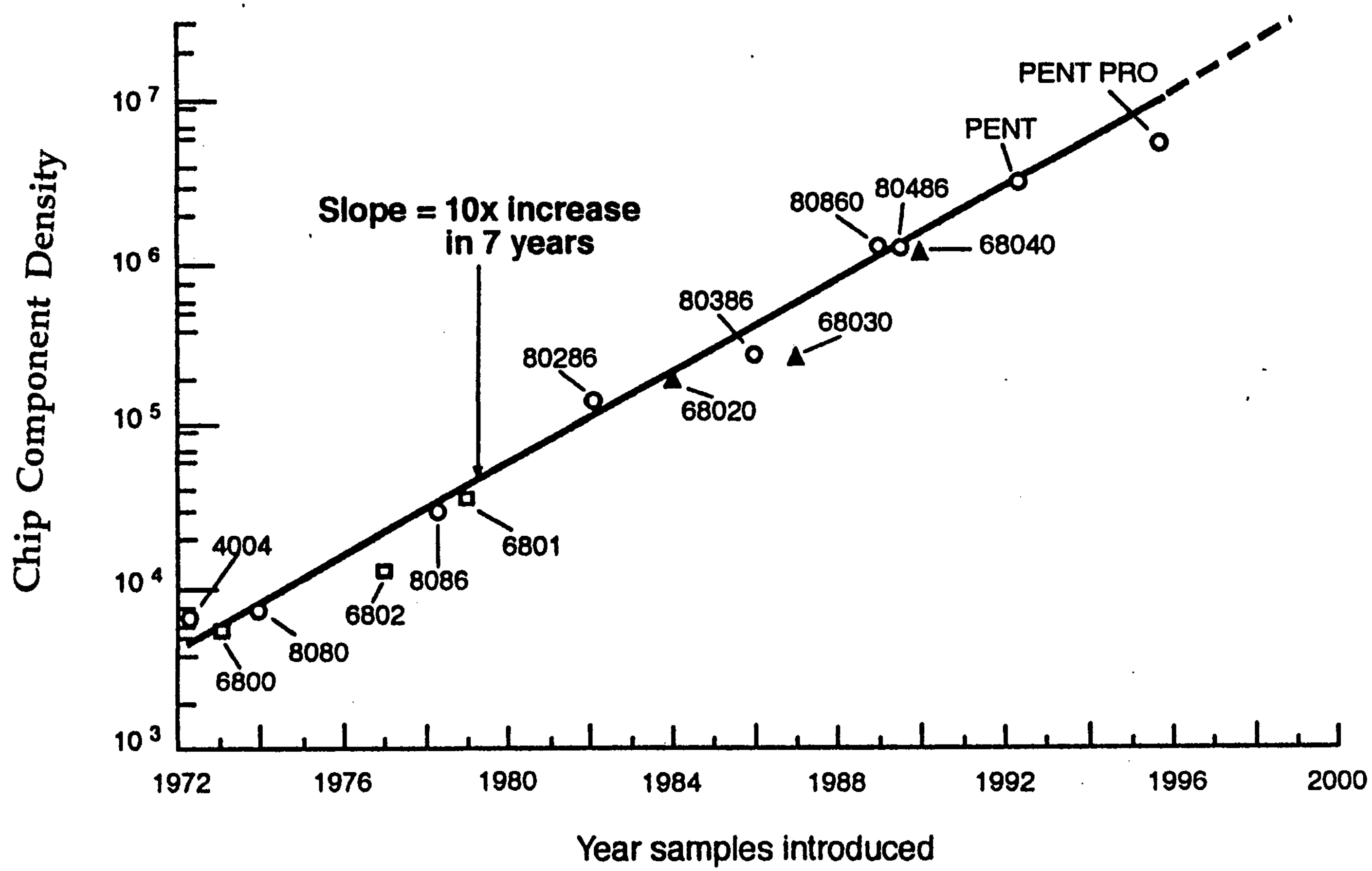

Comparison of Power Requirements for the Land Warrior System and Notional Dismounted Soldier Systems

	Land Warrior in 2001 (Operating Power in Watts)	Commercial Technology in 2001 (Operating Power in Watts)	Commercial Technology in 2015 (Operating Power in Watts)
Computer/Radio Subsystem			
Computer	14.800	0.150	0.010
Hand-Held Flat Panel Display	6.400	0.200	0.007
Soldier Radio			
Receive	1.400	0.100	0.025[a]
Transmit	6.000	1.600	1.520[a]
Squad Radio			
Receive	2.000	--[b]	--[b]
Transmit	12.000	--[b]	--[b]
Global Positioning System	1.500	0.100	0.020
Video Capture	1.000	0.050	0.010
Subtotal	45.100	2.200	1.592
Integrated Helmet Assembly (IHAS Subsystem)			
Laser Detectors	0.600	0.050	0.025
Helmet Mounted Display	4.900	0.220	0.025
Imager	< 0.100	0.050	0.025
Subtotal	5.600	0.320	0.075
Weapon Subsystem			
Laser Rangefinder	0.050	0.050	0.025
Laser Aiming Light	0.075	0.005	0.005
Digital Compass	0.350	0.005	0.002
Thermal Weapon Sight	5.525	1.100	0.160
Subtotal	6.000	1.160	0.192
Wireless Sensor and Display Interconnect	--	0.100	0.050
TOTAL SYSTEM POWER	56.70	3.78	1.91

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Conclusions

Dramatic reductions in power/energy requirements are possible for Soldier

- Clever software
- Higher component density
- Lower voltage
- Clever packaging

Energy/power levels may be reduced to the point where electrical energy may be extracted from human sources for some applications

"DARPA PERSPECTIVE ON POWER TECHNOLOGY"

Dr. Robert J. Nowak

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Arlington, VA 22203-1714

DARPA PERSPECTIVE ON POWER TECHNOLOGY

Defense Sciences Office

Presented to:

<u>Prospector IX</u>
Human Powered Systems
Durham, NC

November 2-5, 1997

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DARPA/DSO
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fax: 703-696-9780
RNOWAK@darpa.mil

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Advanced Energy Technologies

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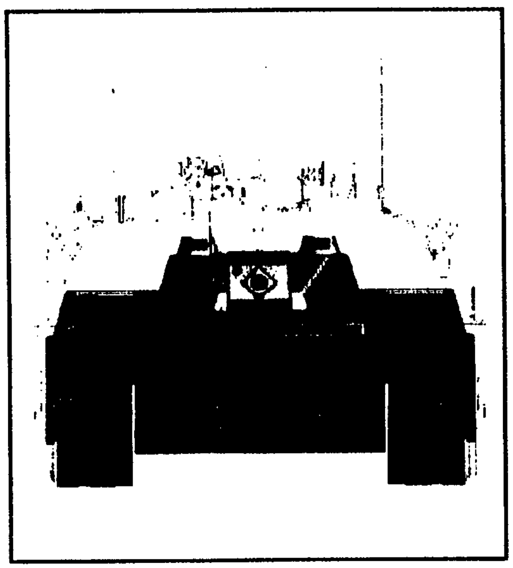
Power for the Military

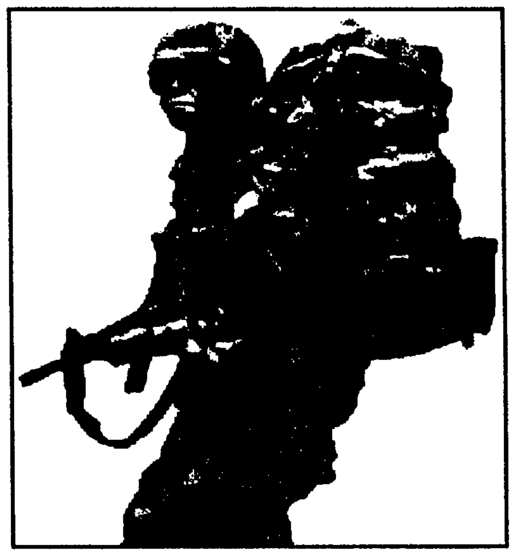
97

Mobile Electric Power
2 - 100 kW



- Silent Watch
- Field Power Stations

Portable Power
50 - 500 W



- Battery Replacement
- Micro-Climate Cooling
- Battery Charging

Energy Harvesting
< 5 W

Micro - Internetted Unattended Ground Sensor

~ 1 "

- Ground Sensors
- Micro - Robots

Mobile Electric Power 2 - 100 kW Fuel Reformer Demonstrations

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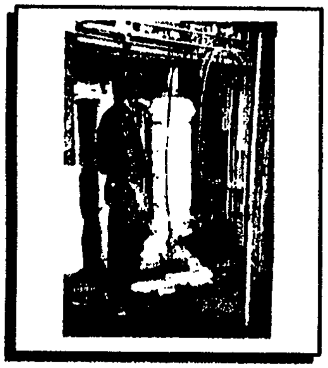
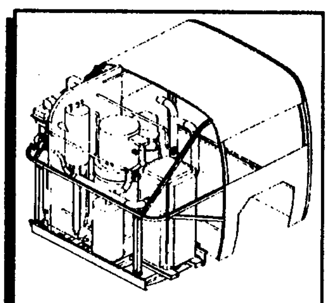
100 kW PAFC

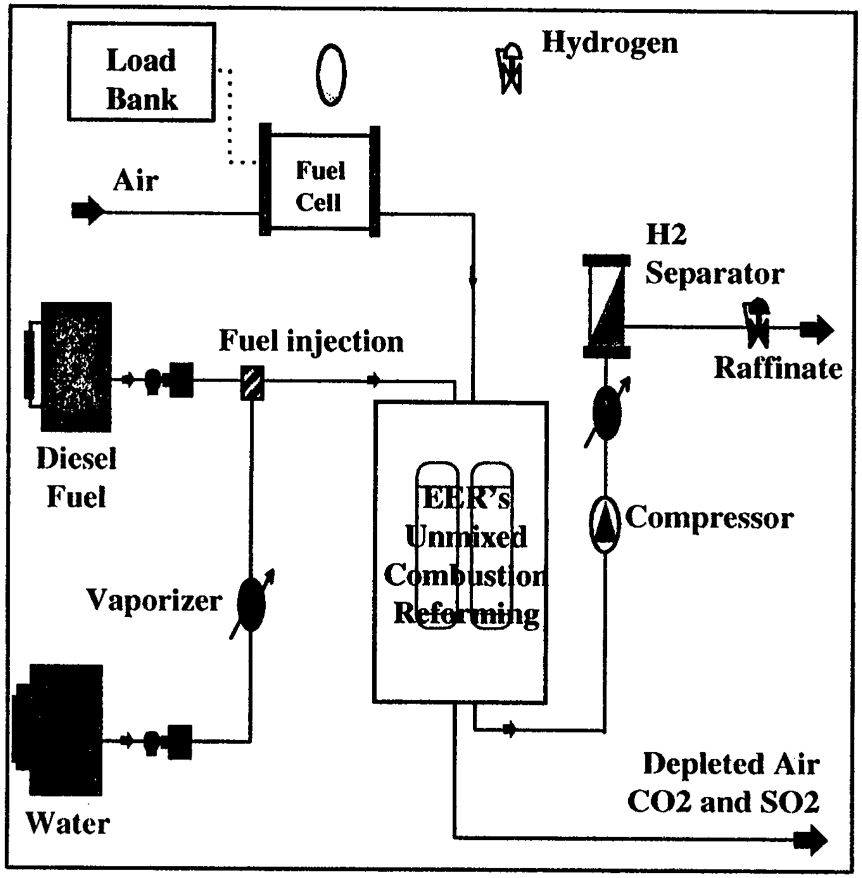


- 14 kW Tested
- 100 kW Fabrication



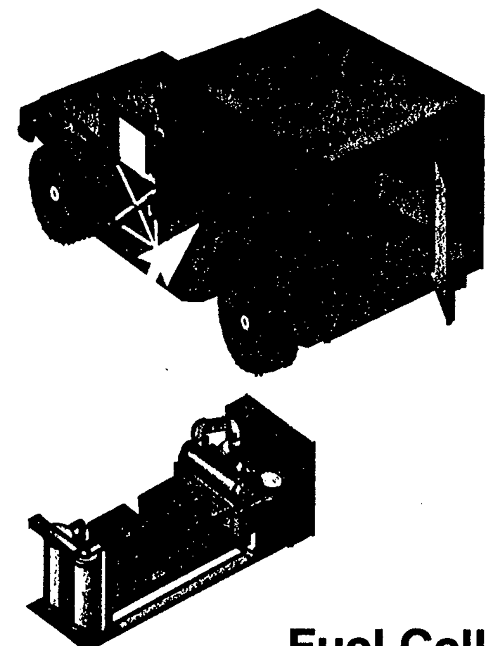
- Georgetown U. Bus

20 kW PEMFC



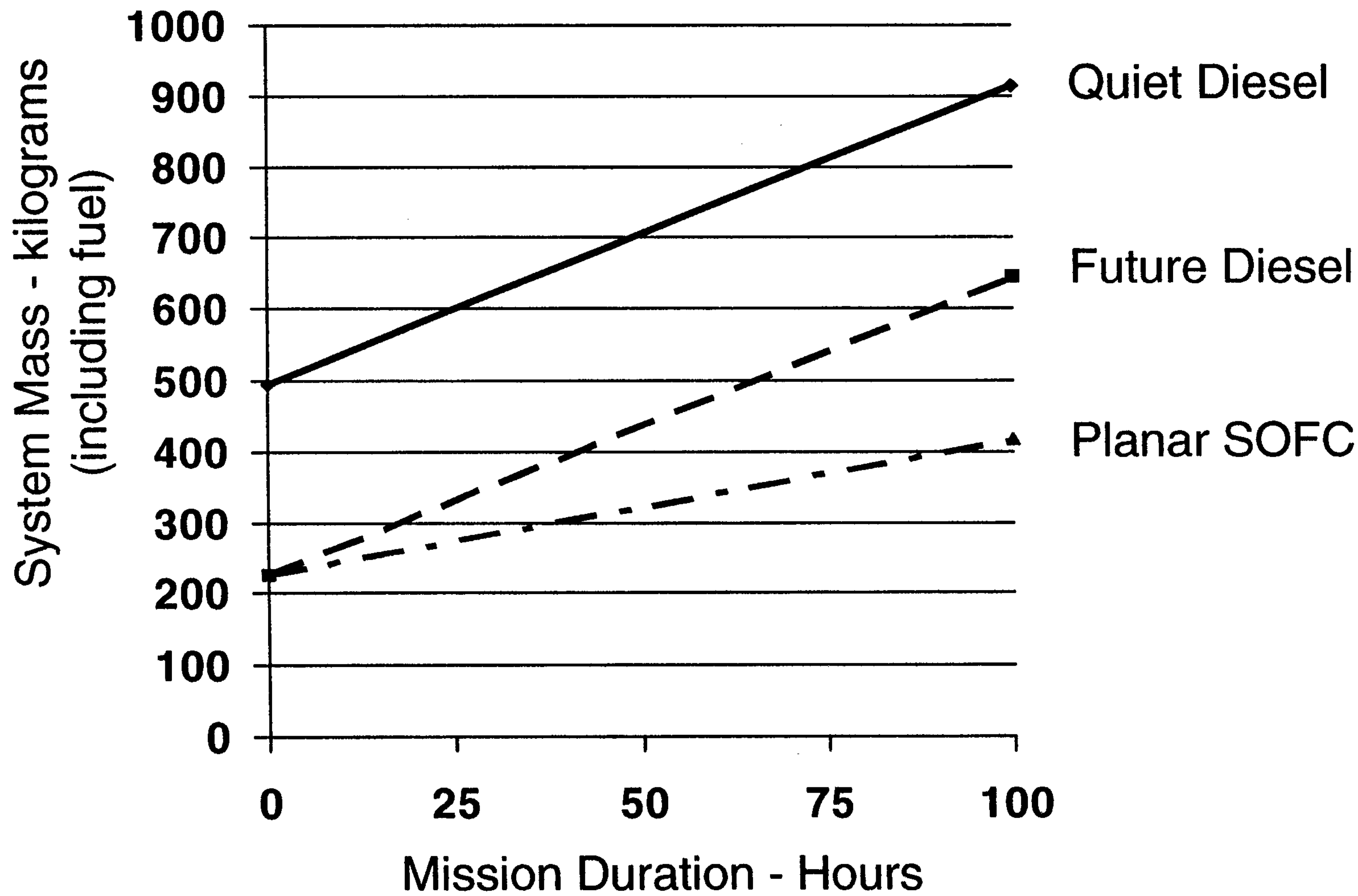
10 kW SOFC

Multipurpose Shelter



Fuel Cell

System Mass vs. Mission Duration
Mobile Electric Power - 10 kW (Logistics Fuel)



Energy Conversion vs. Energy Storage

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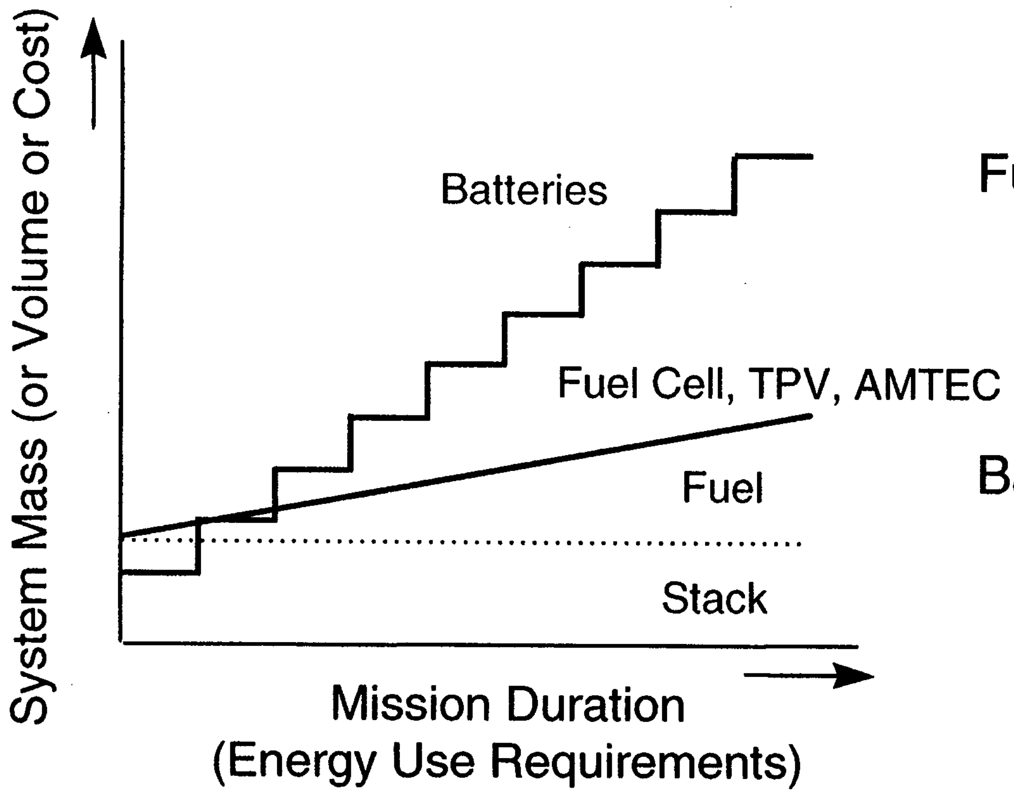

Energy Density of Selected Fuels and Batteries

	Energy Density
Fuel:	
Diesel Fuel/Jet Fuel	12,000 Wh/kg
Methanol	5,000
High Explosive	1,000
Battery:	
Primary Battery (est. max.)	500
Rechargeable (est. max.)	200
Li/SO_2 Battery (primary)	176
Alkaline Battery (primary)	80
Nickel-Cadmium (secondary)	40

Driving Force: Substantially decreased size, weight, and cost with improved safety and environmental compliance → Increased force mobility

Portable Power
50 - 500 W

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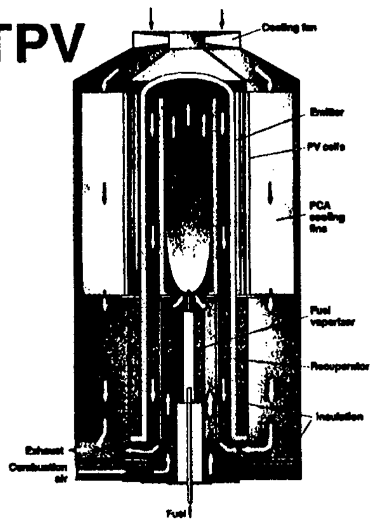
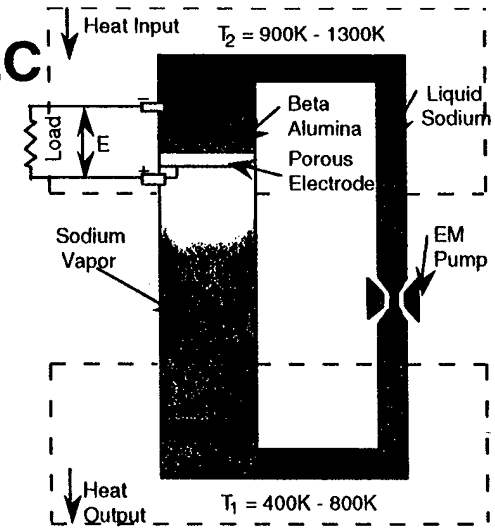
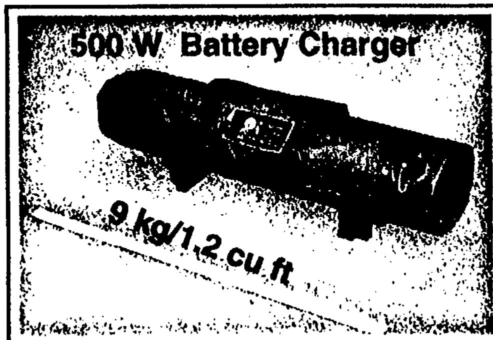
TPV

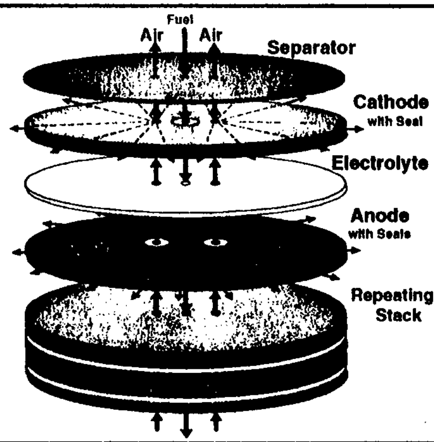


micro-Turbine Generator

AMTEC

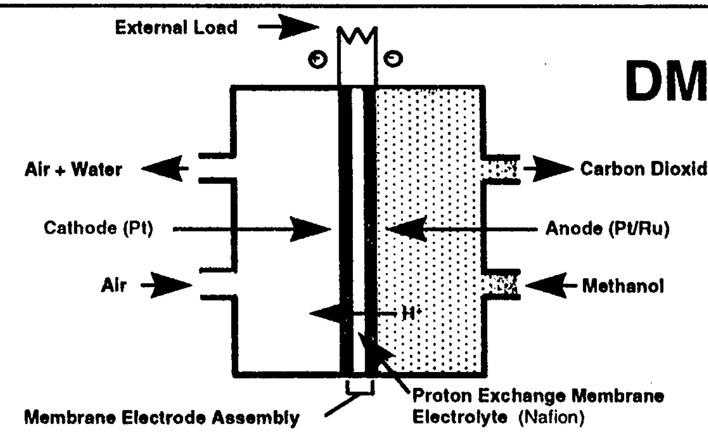






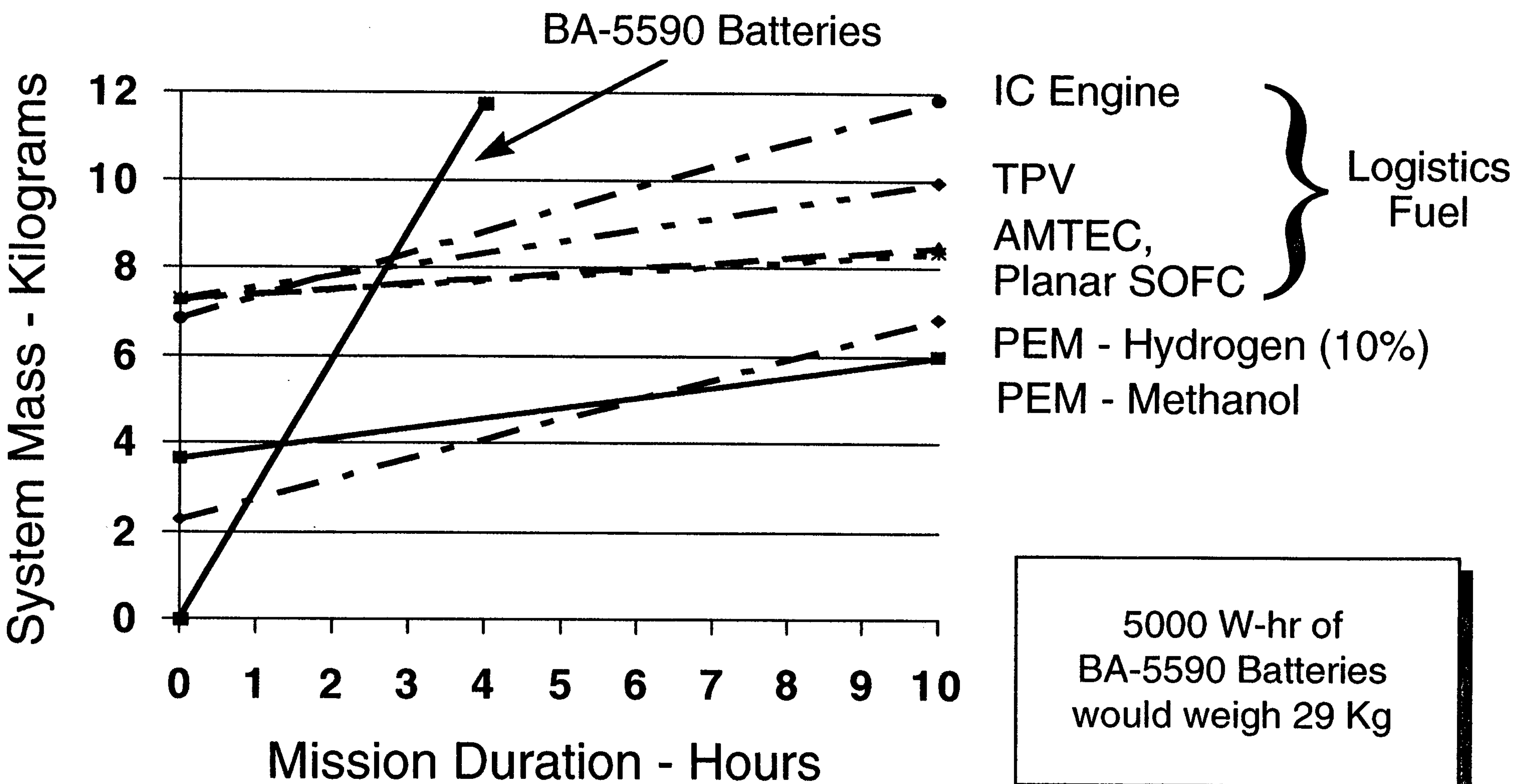
Planar SOFC

DMFC



System Mass vs. Mission Duration
Portable Power - 500 W

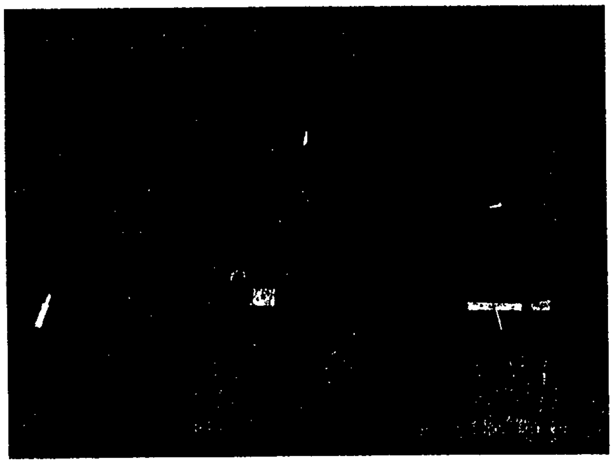
Defense Sciences Office



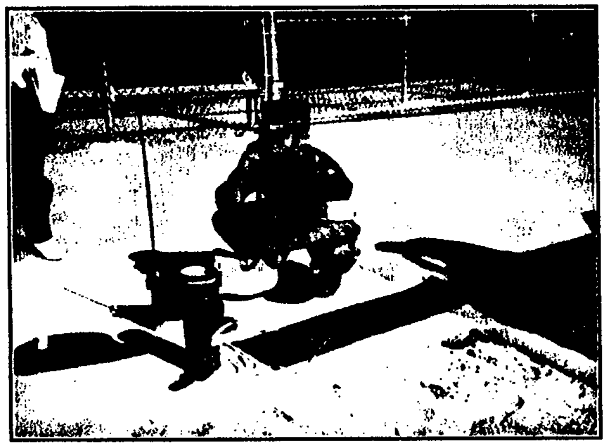
5000 W-hr of BA-5590 Batteries would weigh 29 Kg

Energy from the Environment

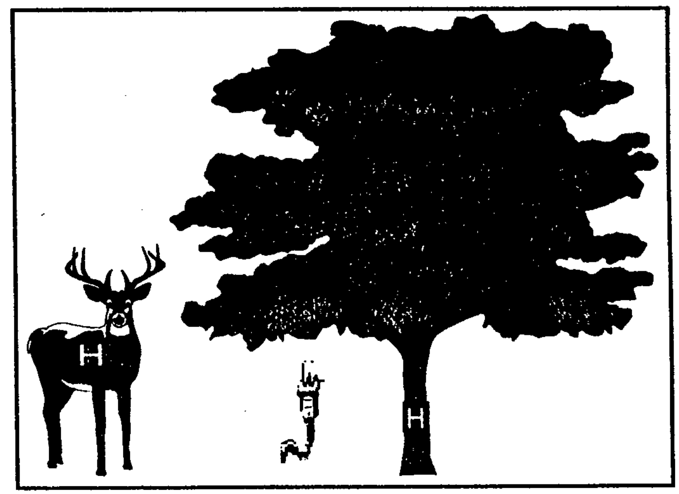
Defense Sciences Office



Marine Corps
Solar - PV; Wind
6 kW



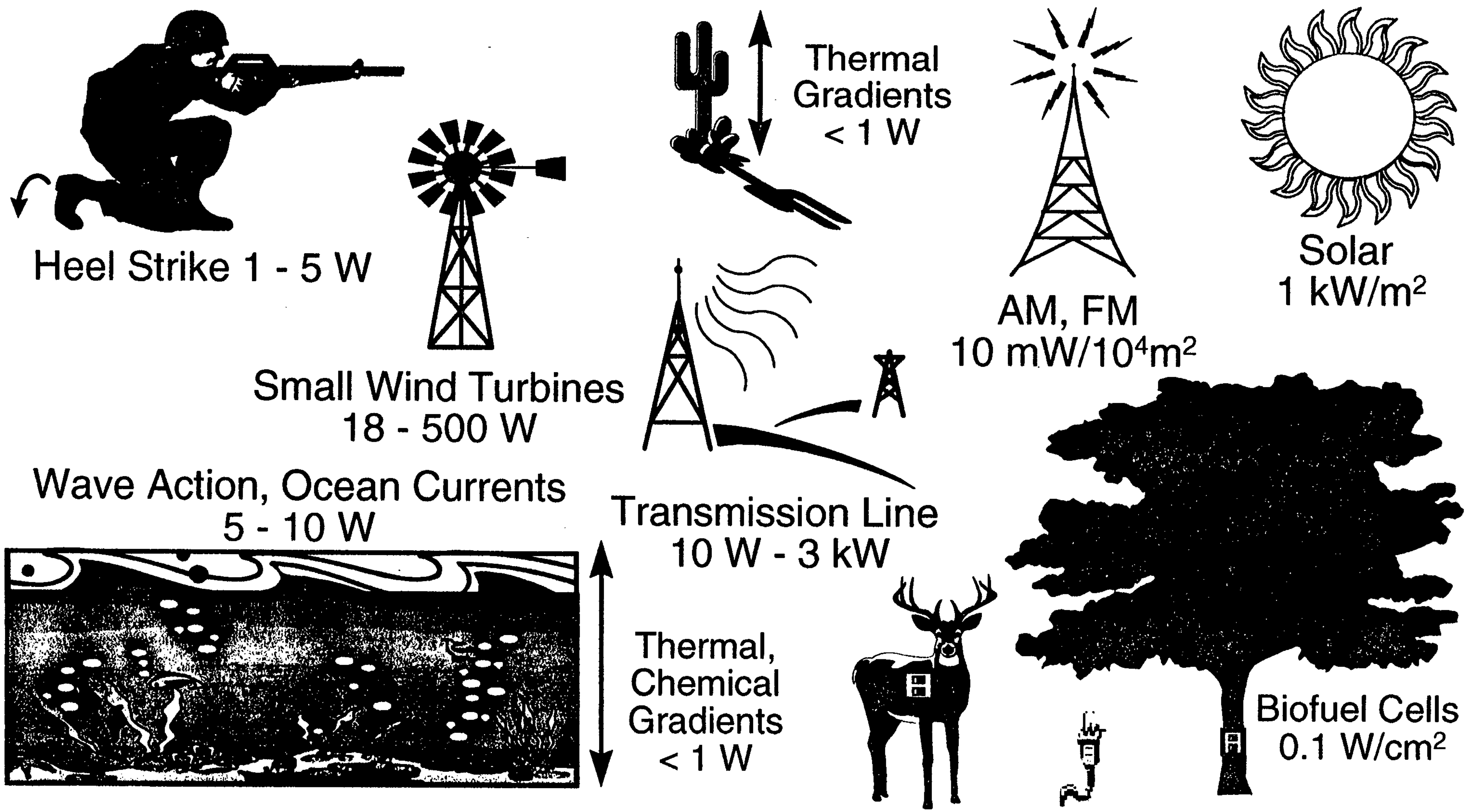
DARPA CIS
Flexible PV
18 W



DARPA Energy Harvesting
Bio, Mechanical, Solar,
Gradients, EM, Transmission
Line, Human Activity, etc.
< 5 W

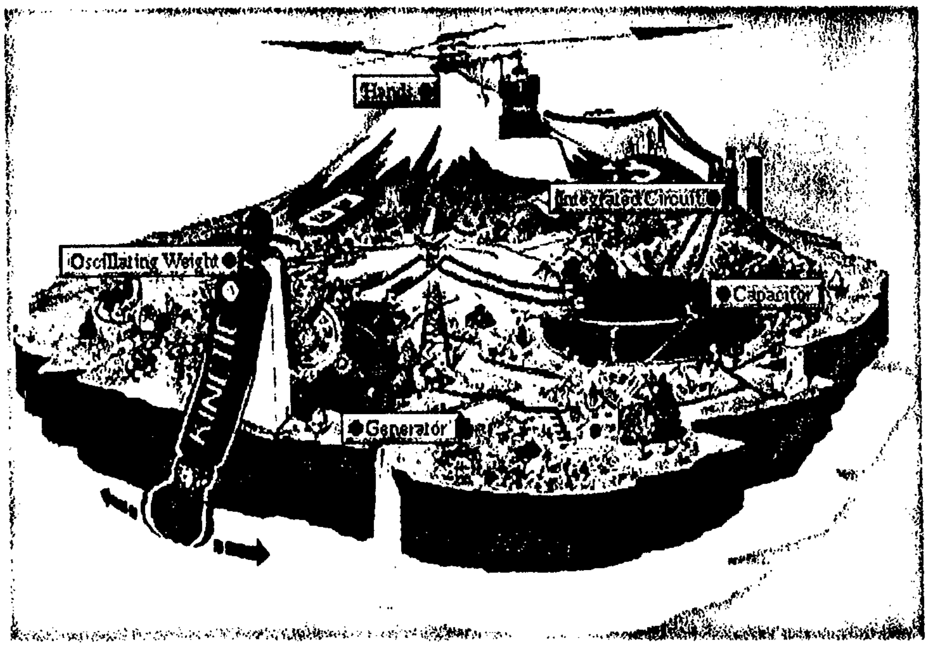
Energy Harvesting - Possible Sources

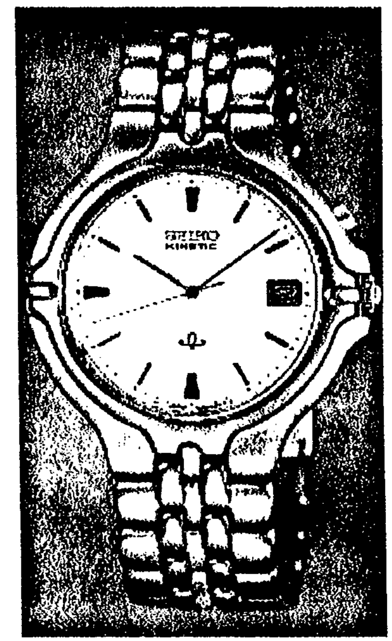
Defense Sciences Office



Energy Harvesting: A Commercial Example

Defense Sciences Office



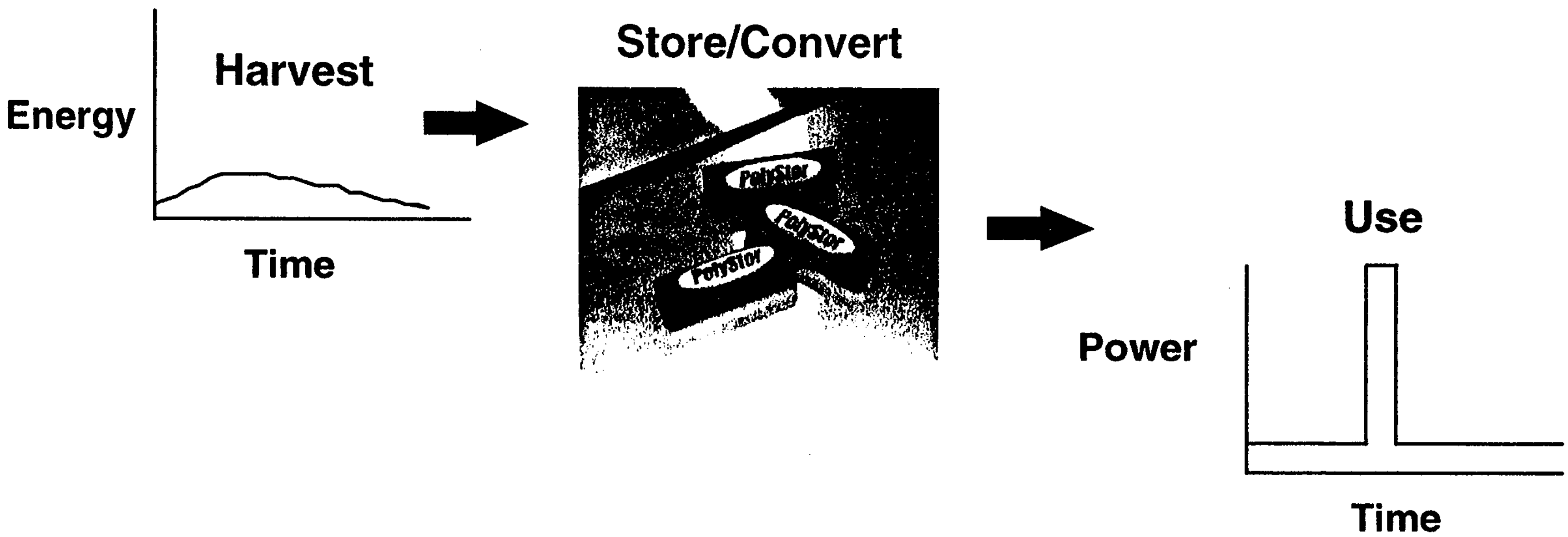


Keys to success

- Mechanical-to-electrical conversion
- Efficient energy storage
- Low power application

Energy Harvesting - Opportunities

- Harvesting Concepts - On and Off the Soldier
- Compatible Storage and Conditioning
- Power Management vs. Duty Cycle
- Materials/Fuels Processing
- Size, Weight (Footprint)



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“SPECIAL OPERATIONS PERSPECTIVE”

Mr. Sal C. Raineri
Ft. Bragg, NC 28307

SOF OPERATES AT LONG RANGE FROM FRIENDLYS AND ONCE INSERTED DO NOT RECEIVE RESUPPLY.

EACH SOF TEAM MEMBER MUST CARRY ALL EQUIPMENT TO INCLUDE FOOD FOR THE DURATION OF THE MISSION.

[WHATEVER YOU CARRY IN YOU CARRY OUT]

SOF MISSIONS: RANGE FROM HOURS -- MONTHS

SPECIAL RECONNAISSANCE	-- 21 DAYS
D.A.	-- HOURS TO DAYS
U.W.	-- LONG TERM
OOTW	-- LONG TERM
LIE	-- LONG TERM
URBAN	-- TERRAIN DEPENDENT

(IN ALL CLIMATIC & TEMPERATURE ENVIRONMENTS)

METHOD OF INFILTRATION

PARACHUTE -- STATIC / HALO / HAHO

AIR / LAND (AIRCRAFT)

SWIM SURFACE / SUB-SURFACE

WALK (CLIMB)

WATER DELIVERY

TAKE THE YELLOW / RED BUS

<u>EQUIPMENT REQUIRING POWER SOURCES</u>

<u>RADIOS</u> -- 2-3 ONE BEING SURVIVAL (EACH)

<u>NVD</u>

<u>GPS</u>

<u>OTPICS</u> -- WPNS / HAND HELD

<u>LASER</u> -- ID AND DESIGNATOR / TGT ACQUISITION

<u>SENSORS: SEISMIC</u> / ACOUSTIC / NEAR-FAR IR (THERMAL)

HAND HELD RADAR LOCATOR AND LASER UTILIZATION

<u>SIGNATURE REDUCTION:</u> ______ ★

<u>WEARABLE COMPUTER</u>

- <u>VOICE TRANSLATOR</u>

<u>FLASH & STROBE LIGHTS</u> (WHITE / IR)

<u>UNDER WATER PROPULSION</u>

- <u>ROBOTICS</u> SYSTEMS

EQUIPMENT LOADS

AVERAGE RUCK SACK -- 115-140 LBS

VESTS / LBE & WPNS -- 50-65 LBS

POWER GENERATION SYSTEMS

BATTERIES

SOLAR

HAND CRANK GENERATOR (FOOT POWERED)

(EACH SOF TEAM MEMBER CURRENTLY CARRIES THREE TIMES NEEDED SUPPLY OF BATTERIES)

(PIEZOELECTRIC FOOT POWERED SYSTEM LOS ALAMOS)

SOLVE POWER GENERATION FOR THE MOST DEMANDING AND DIFFICULT

S.O.F.

YOU SOLVE FOR THE REST OF SERVICES & LAW ENFORCEMENT.

OVERVIEW SESSION 2

"SUO POWER PROFILES - CECOM PERSPECTIVE"

Mr. James E. Stephens

CECOM
Front Royal, VA 22630

SMALL UNIT OPERATIONS
POWER PROFILES - CECOM PERSPECTIVE

PRESENTED TO PROSPECTOR IX WORKSHOP

NOVEMBER 2, 1997

JAMES STEPHENS
US ARMY CECOM
(703) 704-2006
jstephens@belvoir.army.mil

THE POWER SPECTRUM

PORTABLE	GRAY AREA	MOBILE POWER
< 500 WATTS		> 500 WATTS TO 1.1 MW

- BATTERY DOMAIN
  - -- TOO HEAVY
  - -- TOO COSTLY
- EXPLORING ALTERNATE TECHNOLOGY
  - -- NICHES FIRST
  - -- GENERAL USE LATER
- HYDROGEN SUPPLY KEY TO FUEL CELL SUCCESS
- MUST COMPETE WELL WITH OR AUGMENT BATT.

- DIESEL / TURBINE POWERED GENERATORS
- COMPETITORS MUST USE DIESEL FUEL

"Power Revolution a Necessity"

"New Sources of Battlefield Energy Would Have Revolutionary Consequences"

Source: ARMY AFTER NEXT "EMERGING STRATEGY"
DEPUTY CHIEF OF STAFF FOR DOCTRINE, TRADOC

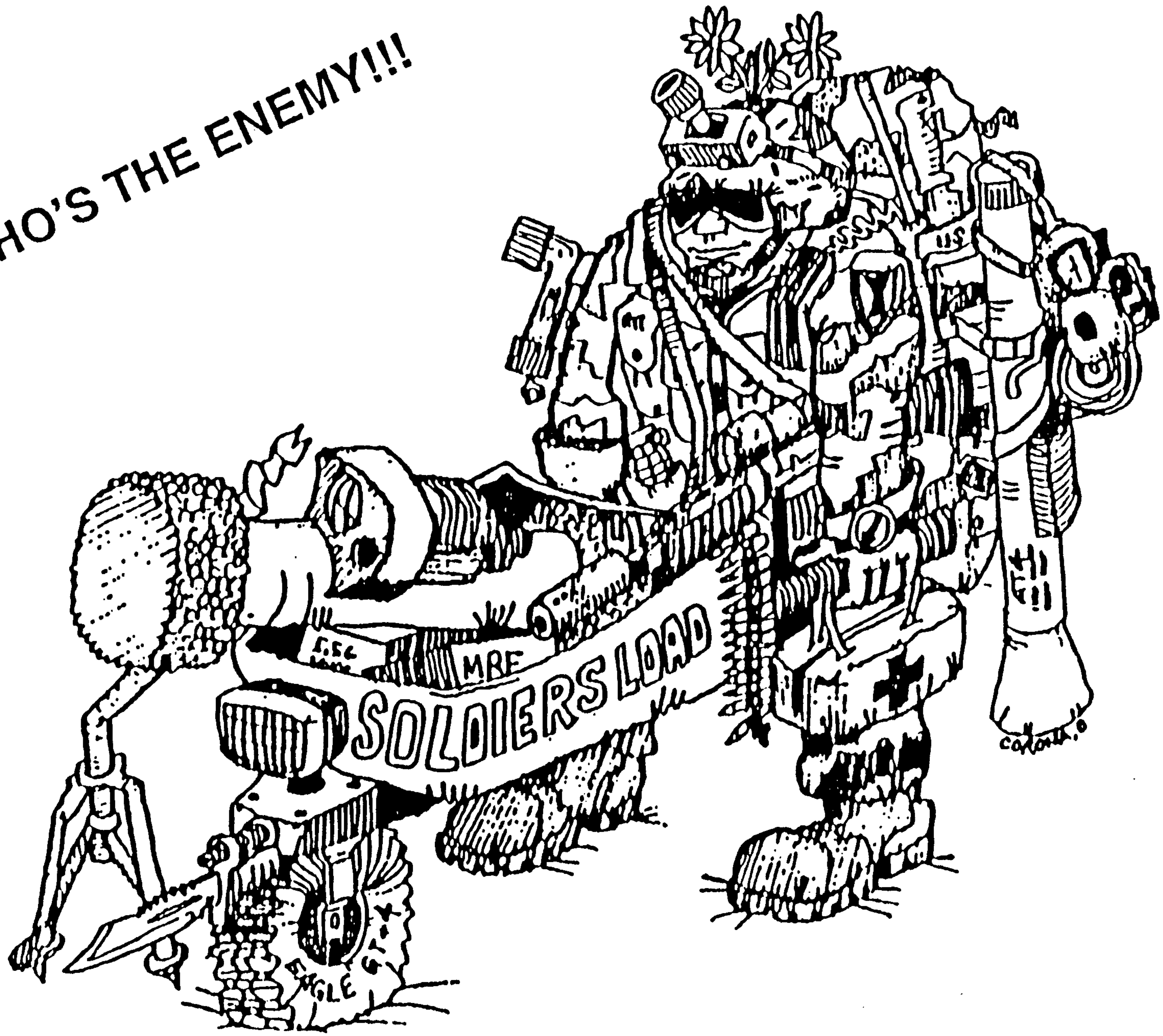
Individual Warfighter System
Size, Weight, and Power

- Soldier Mounted
- < 1 kg
- < 5 watts
- No keyboard
- Very user friendly interface
- Single battery
- Minimal wires
- Plug and play for different applications
- Physically robust

SMALL UNIT OPERATIONS - POWER REQUIREMENT SUMMARY

- AVERAGE POWER DEMAND - 5 WATTS
- PEAK POWER DEMAND - 20 WATTS
- MISSION LENGTH - 7 DAYS
- MISSION DAY PROFILE
  - 20 HOURS ON
  - 4 HOURS OFF
- TOTAL ENERGY DEMAND - 700 WHRS

WHO'S THE ENEMY!!!



REQUIREMENTS: SYNOPSIS

- FEATURES CRITICAL TO SO SOLDIERS: SMALL, LIGHT, CHARGE INDICATOR AND RECHARGEABLE
- INCREASE POWER DENSITY/MAINTAIN COST
- EQUIPMENT LIMITATIONS CAN NOT DICTATE MISSION PLANNING/ ACCOMPLISHMENT
- LIGHTWEIGHT POWER IS AN ALL-OPERATIONS PROBLEM: WAR, OOTW/PEACEKEEPING, AND TRAINING
- POWER SOURCES REQUIREMENTS ARE NOT SOF-UNIQUE, THUS LEVERAGING NEEDED
- LIGHTWEIGHT POWER IS 3RD HIGHEST TECHNOLOGY PRIORITY OF CINCSOC

DISMOUNTED / REMOTE SENSOR SUITES POWER REQUIREMENTS SUMMARY

- POWER REQUIRED <1 - 100 WATTS
- VERY HIGH PEAK POWER TO AVERAGE (1500 TO 1)
- 240 WHRS - 30 KWHRS
- MISSION DURATION - 7 TO 90 DAYS
- UNATTENDED MISSIONS
- SOME MISSIONS ARE EMPLOY AND FORGET
- DEPLOYED FROM AIR OR MANUALLY

Soldier Power System Requirements

- *Small, light weight*, soldier portable
- Continuous power for extended periods
- Necessary power for standard and future equipment
- *Undetectable*: silent, odorless, easily concealed
- *Safe*: stable materials, less hazardous
- Easily supported, maintained
- Durable, rugged, NBC *survivable*
- Modular, interconnective capability
- Operate under all conditions: ECM, smoke, aerosols, fog, rain, haze, dust, wind, snow, icing, NBC, heat, cold, etc.....
- Compatible with full protective posture
- Decontaminable w/o efficiency loss

(Source: MNS for Soldier Power System)

Dismounted Battlespace Battle Lab

[redacted]

- MISSION CANNOT BE CONSTRAINED BECAUSE OF POWER LIMITATIONS (PERFORMANCE)
- SOLDIER MOBILITY MUST NOT BE HAMPERED (WEIGHT)
- UNITS MUST BE ABLE TO TRAIN AS THEY FIGHT (COST)
- SOLDIERS MUST HAVE SAFE POWER (SAFETY)

POWER...
WHEN WE NEED IT...
WHERE WE NEED IT!!

SUMMARY OF POWER / ENERGY PROFILES FOR VARIOUS INDIVIDUAL SOLDIER MISSIONS

APPLICATION	POWER (WATTS)	ENERGY (WHRS)	C0MMENT
SPECIAL OPS	50	2500 - 30,000	SOME SET/FORGET MISSIONS.
SMALL UNIT OPERATIONS	5 / (25 PEAK)	700	LIGHTWEIGHT
SENSOR SUITES	5 / 50 / 100	240 - 30,000	LONG MISSIONS
SOLDIER POWER	50 / 150	1200 - 2,500	MUST AUGMENT BATTERIES

POWER MANAGEMENT DEFINITION

Improve the warfighter's capabilities by lightening his load and lessening the logistics burden by:

1) managing power usage on the battlefield

2) using advanced power generation

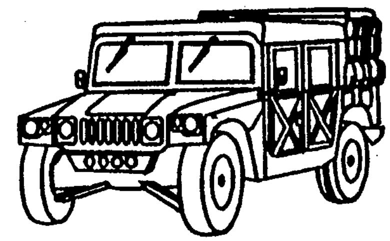
3) reducing equipment power consumption.

INCENTIVES FOR POWER MANAGEMENT

CONSERVE ENERGY IN MANPORTABLE EQUIPMENT

- Lighten soldier load (sustainment)
- Longer mission times
- Enhanced functional capability
- Simplified battery replacement/disposal

OPTIMIZE VEHICULAR PLATFORMS



- Electronics require less volume
- Smaller generator required
- Smaller air conditioner
- Greater capability and reliability in smaller system weight/volume
- Silent Operations

REDUCE O & S COSTS

Hunn1023/102097/PPTFILES/HEUNER/SP

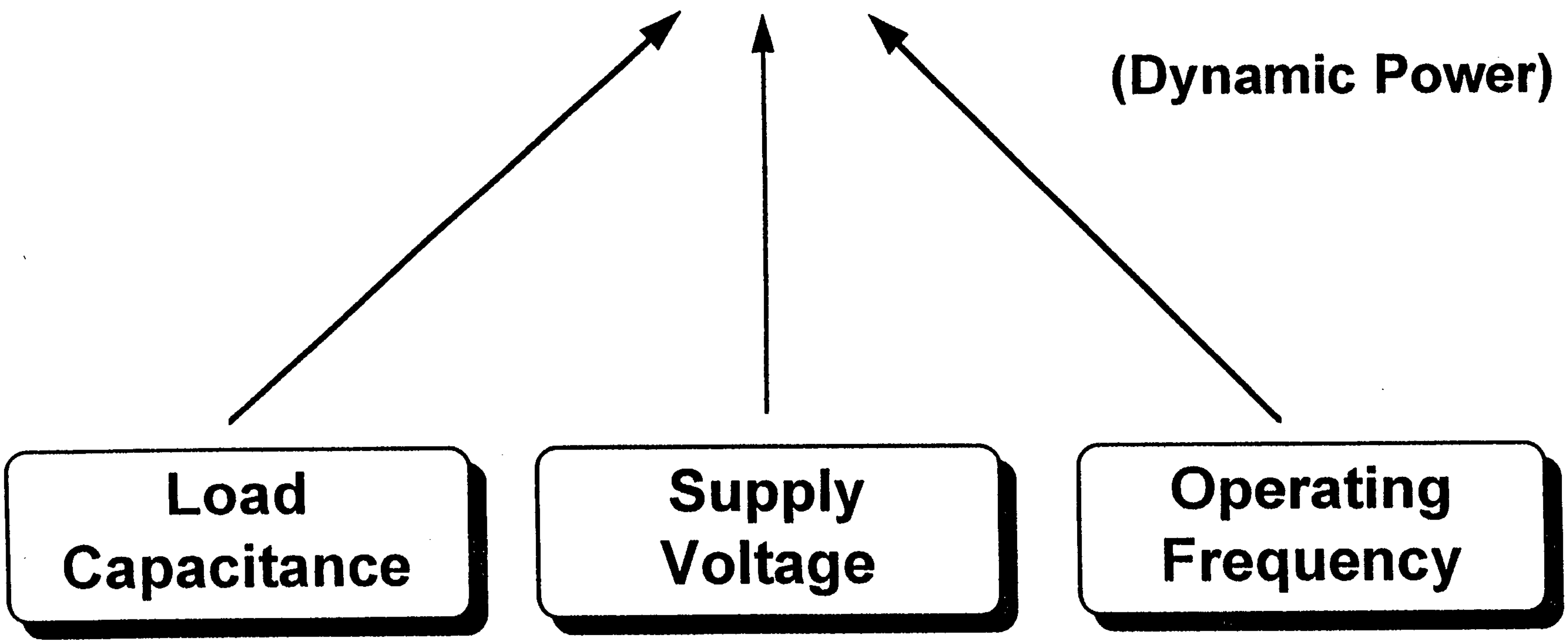
KEY PATHWAYS FOR POWER REDUCTION

- Low Power Electronics (i.e. low operating voltage)
- Smart Electronic Sub System Management (i.e: Sleep modes)
- System Optimization (i.e: antenna requirements, display requirements)

LOW POWER ELECTRONICS

$$P = C\,V^2\,f$$

(Dynamic Power)



POWER DEMAND AND POWER SUPPLY

Front End Power Analysis of Individual Soldier	Task Force XXI	Landwarrior	Small Unit operations	Army After Next
	1995	2000	2005	2010

	1995	2005	2010
Power Demand			
	50 Watts 1200 Whrs 2-3 Day Missions (Digital Equip Operates @ 5.0 volts)	25 Watts 1000 Whrs 3 + Day Missions (Digital Equip Operates @ 3.3 volts)	5 Watts (averg) 25 Watts (peak) 700 Whrs Extended Missions - >7 days (Digital Equip Operates @ 0.9 volts)
Power Supply	Primary Batteries (170 Whr/Kg)	Primary Batteries & Rechargeable Batteries BB390A/U - 96 Whr, 1.75 Kg BB2847/U - 25 Whs, .38Kg Hybrids	Batteries/ Robust Hybrids
<u>Example</u> .1 m^2 Solar Panel @ 19 Watts	38% of Mission	76% of Mission	380% of Mission

POWER DEMAND AND POWER SUPPLY
(Cont.)

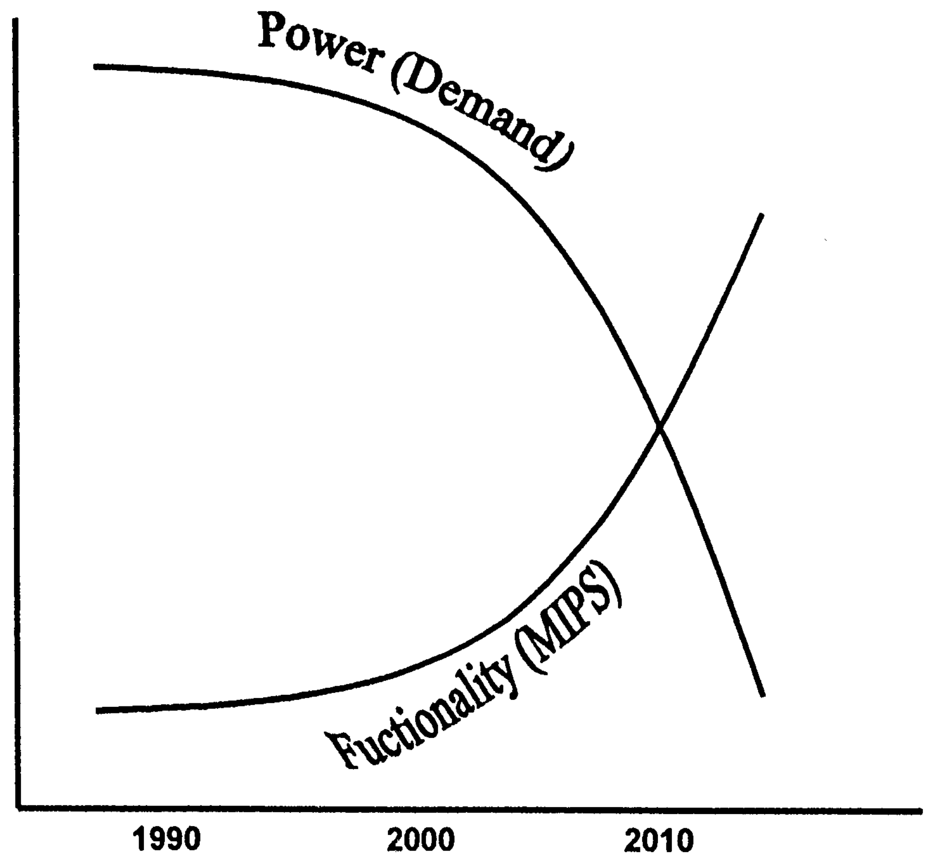
★ Mission length will not be constrained by power supply

★ Functionality will increase while power demand drops dramatically

★ Indigenous / Reliable Power Sources can be tapped to supply much (perhaps all) of power budget.

★ Robust Power Supply Hybrids needed to orchestrate:

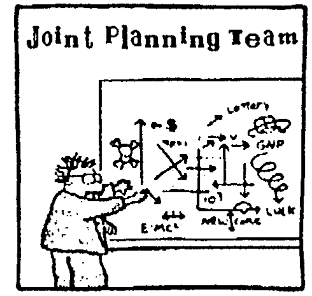
- *Battery Charging*
- *Energy Management*
- *Power Distribution*



“NASA INVESTMENT IN SPACECRAFT SYSTEMS TECHNOLOGY”

Mr. Ronald J. Sovie

NASA Lewis Research Center
Cleveland, OH 44135



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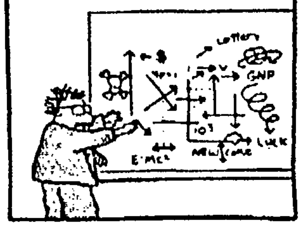
The NASA Spacecraft Systems Technology Program

R. J. Sovie
NASA Lewis Research Center

November 3, 1997

RJS98-001.1

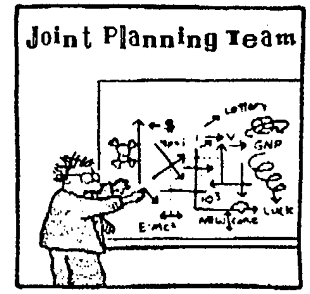
Joint Planning Team



What We Will Discuss

- **Spacecraft Systems Technology Program Elements**
  - Content
  - Milestones
  - Budget
- **Specific Technologies**
  - Relevant
- **Concluding Remarks**

RJS98-001.2

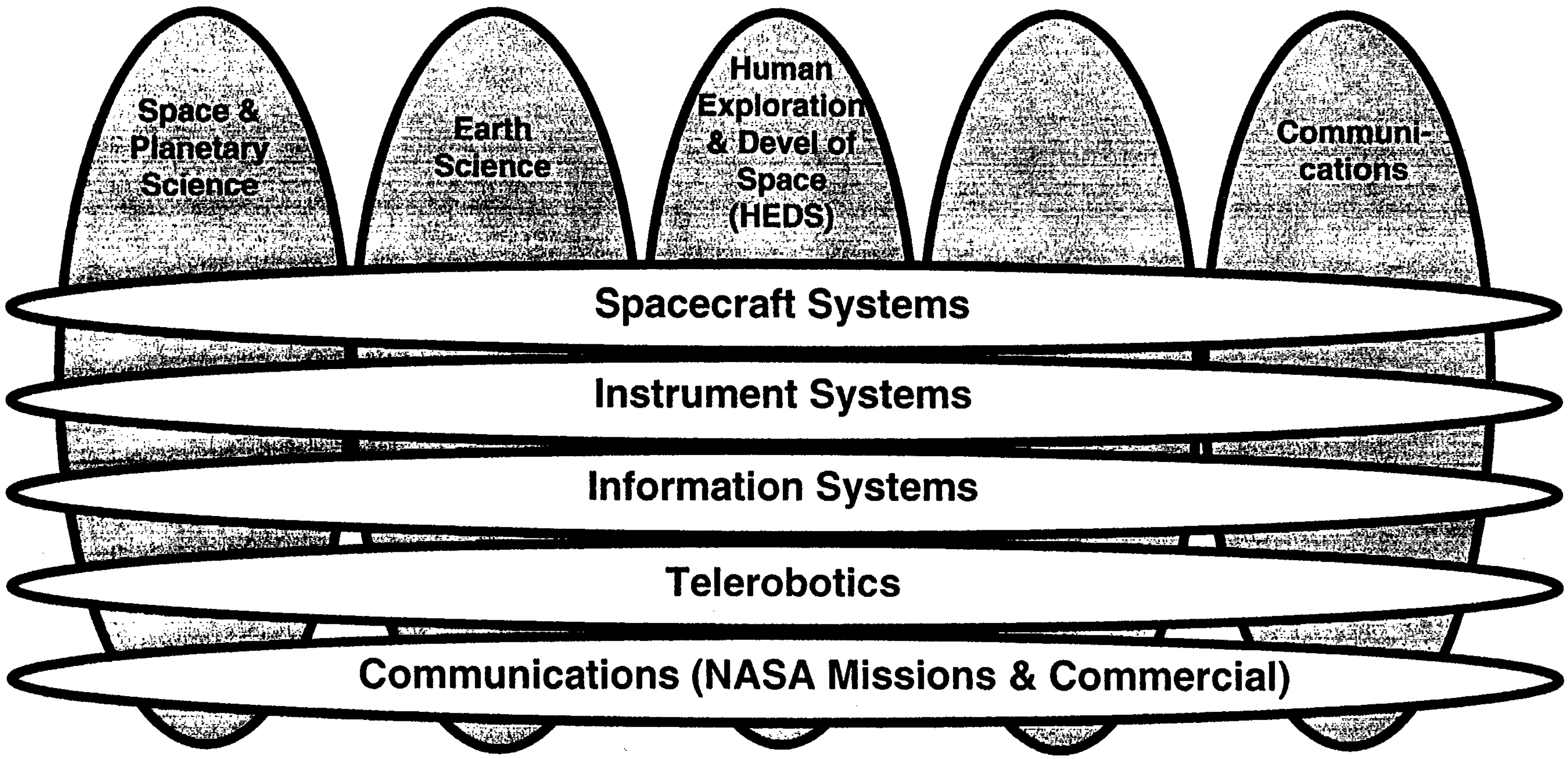


Spacecraft Systems Technology Program

- **Broad-based technology program that supports:**
  - Planetary Missions
  - Mission to Planet Earth
  - Human Exploration
    - **ISS**
    - **Shuttle**
    - **Lunar-Mars**
    - **Suits**
  - Aeronautics
  - Commercial Communication
  - DOD
- **Cross-Cutting Spacecraft Systems Budget**
  - ~ $40M/year ↓

RJS98-001.3

Cross-Cutting Technology Areas to Respond to Customer Technology Product Requirements



Note: Spacecraft Systems includes: Space Environment & Effects; Structures & Materials; Thermal Management; Power & Propulsion; Avionics; Design Tools

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Spacecraft Systems Contains 4 Disciplines & Are Managed Using Integrated Product Development (IPD) Teams

Spacecraft Systems Joint Planning Team

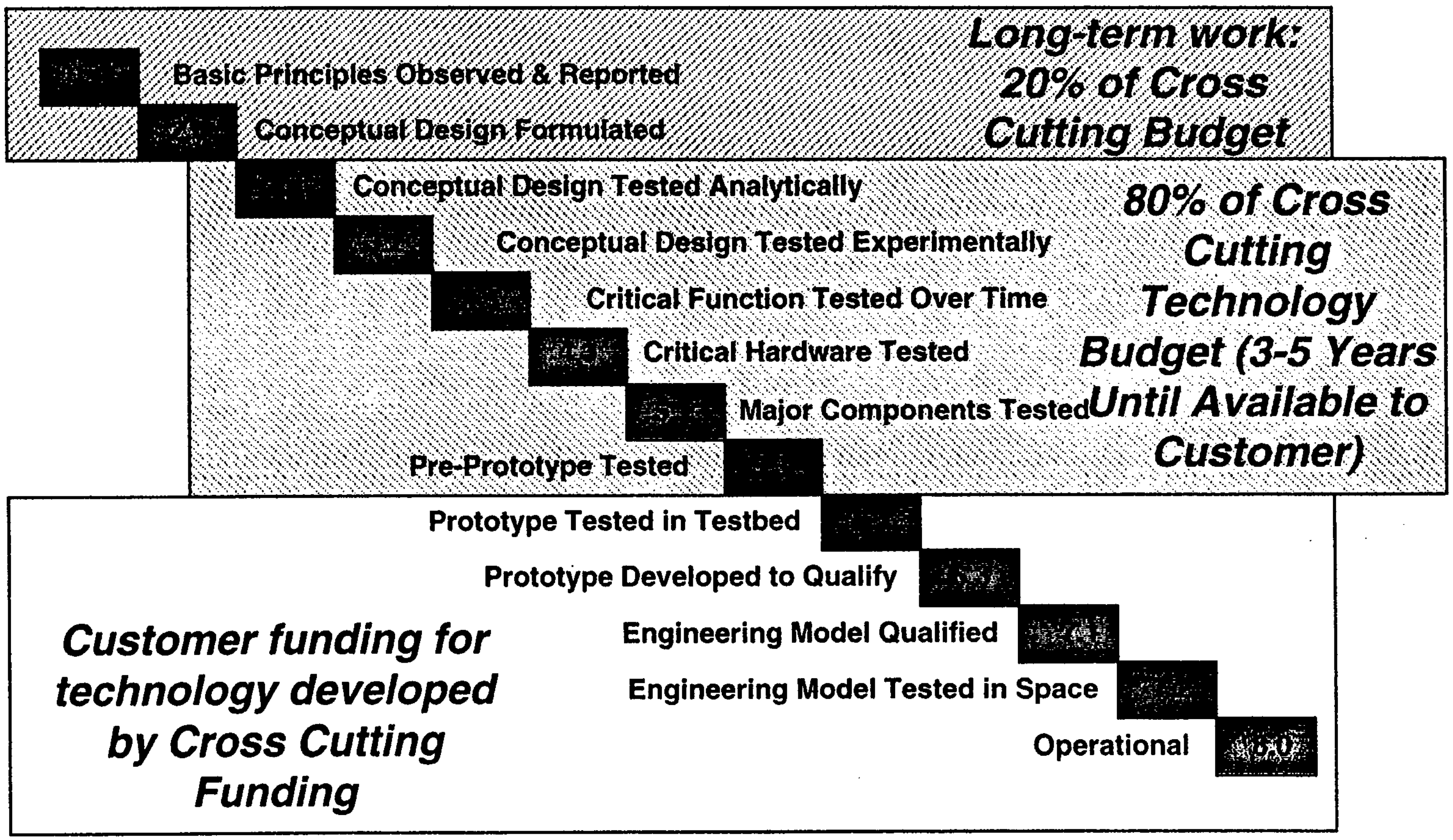
IPD Team 1:
- *Power Generation, Management, & Distribution*
- *Power Storage & Reliability*
- *Thermal Control*
- *On-Board Propulsion*

IPD Team 2:
- *Light Weight & Multi-Functional Sturctural Systems*
- *Breakthrough Materials*
- *Deployable & Inflatable Structures*
- *Structural Dynamics & Geometry Control*
- *Space Environments & Effects*

IPD Team 3:
- *Design & Simulation Tools*
- *Collaborative Design Infrastructure*
- *Microspacecraft Testbed*

IPD Team 4:
- *Systems & Advanced Architectures*
- *Instrument & Flight System Computing*
- *Guidance, Navigation, & Control*
- *Data Handling & Storage*
- *Packaging*
- *Low Power Electronics*

Technology Readiness Levels for Technology Products



Spacecraft Systems

Mission

95 96 97 98 99 01 05

COMMERCIAL (COMMUNICATIONS =>
EOS-AM =>PM => CHEM
REMOTE SENSING => MARS SURVEYOR => SIRTF ASEP => TOPS
SSTI => "DISCOVERY SERIES" =>
NEW MILLENNIUM =>

Power Systems

High Cycle Life Batteries for LEO (2X Whr/kg)
Li Batteries (Small S/C & Planetary Appl)
Compact Batteries (1/2 Vol)
Hi-Efficiency, Low Cost PV Arrays (1/2 Area, 1/2 Wt, 1/3 Cost)
Wide Temp. Solid State Power Electronic (-10°K to ~500°K)
Hi-Temp for Compact Power Systems
Lo-Temp. for Deep Space Ops
(10X Increase in W/cm3)
Adv. Low Vibration Refrig. Freezer
Hi-Efficiency Radioisotope

Integrated Power & Electric Propulsion

1/3 Weight
1/3 Size
1/3 Cost
3X Life

On-Board Propulsion

Adv. Hi Isp Chemical Prop. for Large Delta V
Low Cost "Clean" Monoprop for Small S/C Orbit Insertion & Contro
Electric Propulsion for Small Size, Lt. Wt.
Low Power Micro-elec., <.001 lbf for Vernier Control
Primary Electric Prop

Avionics

Fault Tolerant, Self Repairing Architecture
Fully Modular "Tailorable" Des
On-Board Autonomous Navigation
- Rendezvous & Landing
Miniature (MEMS) Components
On-Board "Health Management"
Hi-Speed Lt. Wt. Low Power Flt. Computer (GFlops, TBytes)
"Computer on Chip"
Multiprocessor Distrib Sys
Optical Data System

100X Faster
10X Smaller
Autonomous Ops.

Structures, Materials, & Space Environmental Effects

Control Structure Interaction
Jitter Suppression
Precision Pointing
Reliable Inflatable/Deployable Structures/Mecha
Integrated Design Methods for Small S/C
Reduced Space Environmental Effects
Accelerated Materials/Structures Qualification

1/4 Cost Due to Structural Behavior & Space Environment

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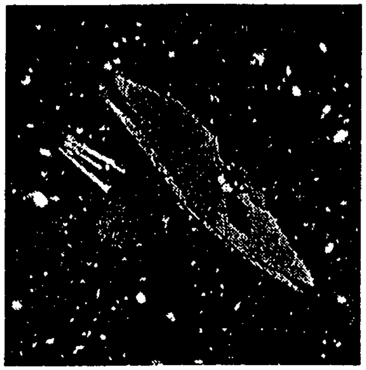
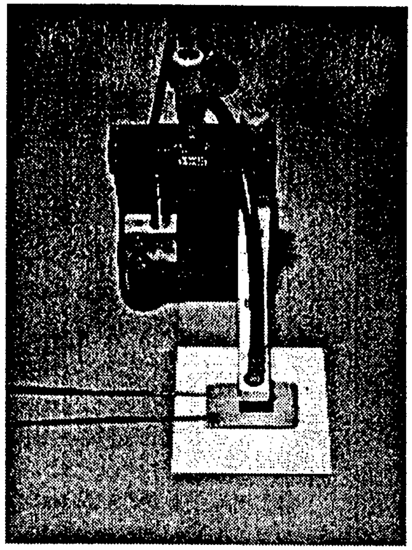
Structural Dynamics & Geometry Control



Next Generation Space Telescope



THUNDER Long-Stroke Actuator

Applications for Future Space Missions:
Low-cost, lightweight structures with integrated efficient actuation and controls for on-orbit correction of geometry errors and changes and suppression of dynamic response

Applications for Ground:
Smart structures that adapt to changing environmental conditions for aircraft, buildings, bridges

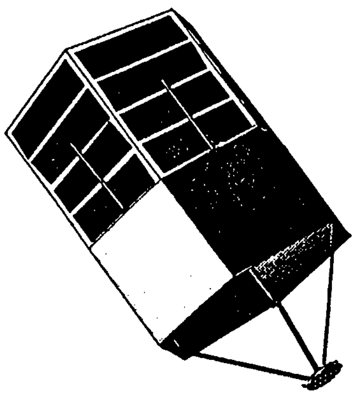
Objectives:
- Cryogenic and high temperature actuator capability
- 10x improved dynamic actuator life and efficiency
- Efficient, affordable long-stroke actuators for instrument scanning, optical positioning, interferometer delay lines

Approach:
- Develop efficient motorless actuators for positioning and motion suppression in extreme environments
- Develop system level methods for vibration suppression and precision pointing when using flexible components
- Validate on focus testbeds

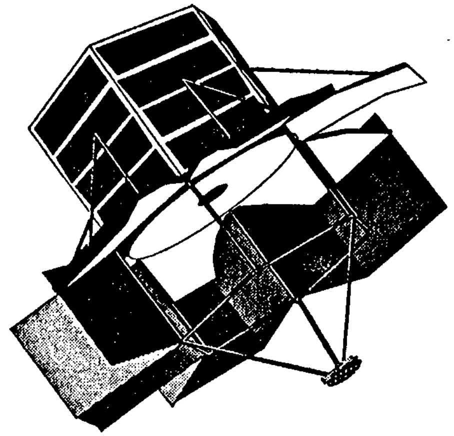
Deliverables & Schedule:
- Complete characterization of THUNDER & Rainbow actuator concepts — Q2 98
- Demonstrate cryogenic position-hold actuators — Q1 99

Deployable & Inflatable Structures

LIDAR Photon Collector



Telescope packaged



Telescope deployed
(sun shroud partially removed)

Applications for Future Space Missions:
Enables launch in small spacecraft for missions requiring precision large apertures
- Interferometers
- NGST
- LIDAR
- Radiometers

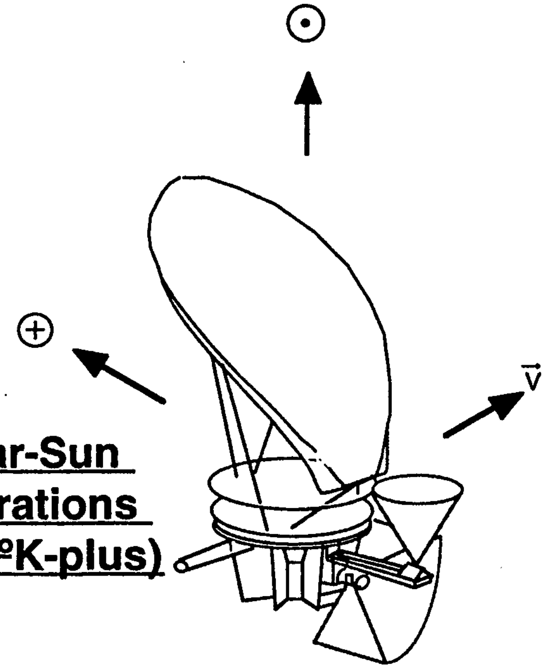
Applications for Ground:
Field deployable tracking and communications systems

Objectives:
Precision deployable structures for large apertures to achieve 10X reduction in launch volume, > SOA performance

Approach:
- Develop deployable 2.5 m photon collector , 50 kg mass, 1.4 m^3 stowed volume (LIDAR focus)
- Develop inflatable electromagnetic wave guide test article for materials and modeling tools evaluation
- Quantify and correct on-orbit dimensional errors through ground and flight experiments

Deliverables & Schedule:
- Complete low-cost composite curved reflector panels Q1 98
- Complete microdynamic testing of deployable truss Q2 98
- Complete inflatable wave guide proof-of-concept Q3 98
- Verify performance of materials & models on inflatable waveguide POC Q3 99
- Complete proof-of-concept LIDAR photon collector and demonstrate predictable performance Q2 00
- Complete prototype deployable telescope and demonstrate optical performance Q2 02

Breakthrough Materials



Near-Sun Operations (2000ºK-plus)

Applications for Future Space Missions:
- Carbon-carbon composites for near-Sun and outer planet missions
- Polymers resistant to space environment for inflatable structures & MLI
- Microcomposite materials for tailored thermal & electrical properties
- Lightweight radiation shielding materials

Applications for Ground:
High-speed aircraft structures
Thermal protection for RLV

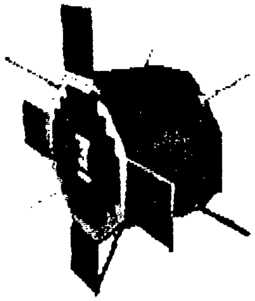
Objectives:
- Lightweight materials and affordable fabrication methods to provide multifunctional shields and precision structures for extreme environments
- Tailored material properties for combined functions and efficient operation
- Materials robust to space environment

Approach:
Develop and test:
- carbon-carbon materials for precision high-temperature structures
- polymers resistant to radiation
- low CTE microcomposite materials for precision mechanisms
- multifunction integrated structural components

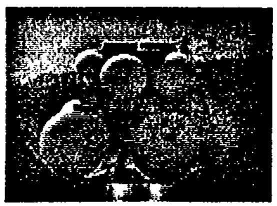
Deliverables & Schedule:

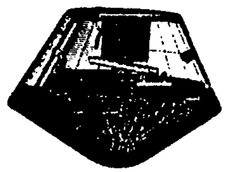
• Transfer soluble imide-based circuits to industry	Q2 98
• Low CTE microcomposite for moldable mechanisms	Q3 98
• Carbon-carbon-sensorcraft frame	Q4 99
• Neutron & conformal radiation shielding materials validated	Q4 99

Lightweight and Multifunctional Structural Systems



<u>Gas & Aerosol Monitor System (GAMS)</u> Solar Occultation Sensorcraft 60Kg, 75W,0.1m^3, $2M ea.





Sample Return In-transit Protection

<u>Applications for Future Space Missions</u>:
Low cost multi-use sensorcraft components and structural hardware integration concepts for extreme environments and distributed networks

<u>Applications for Ground</u>:
Aircraft structures, industrial equipment

<u>Objectives</u>:
Reductions of, relative to the state-of-the-art, 3x system packaging volume, 3x structural mass that is functional during launch only, and 10x cost via fabrication economies and predictable in-space performance/reliability. Sensorcraft structures for extreme thermal and radiation environments.

<u>Approach</u>:
Develop highly integrated subsystem structures that incorporate tailored structural, thermal, electrical, electromagnetic, and radiation-shielding properties in advanced composite and polyimide materials. Validate concepts in focus ground testbeds and flight experiments. In FY 98, increase emphasis on high-temperature and high radiation applications.

<u>Deliverables & Schedule</u>:
- Complete GAMS sensorcraft design Q1 98
- Complete benchless-optics sensorcraft testbed (FTS) Q3 98
- Complete integrated radiation shielding and structure proof-of concept tests Q3 99
- Complete carbon-carbon sensorcraft design for high-temperature focus application

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Structures, Materials, Mechanisms, SEE Technology Roadmap

FY	98	99	00	01	02
Lightweight & Multifunctional Structures & Components	GAMS Sensorcraft Design	Benchless FTS Structure	Validated analysis of Low-cost composites High Temperature Sensorcraft	Extreme Temperature Precision Structures Smart Composites	2X increase post-launch functionality of structural mass (MTPE spacecraft, aeroshells, solar observers, LIDAR)
Breakthrough Materials	Low-cost Carbon-carbon Components Materials Assessment for Inflatables	Tailored Microcomposite Mechanisms	Composites with Integrated Thermal & Radiation-Shielding	Films Tailored for Inflatables	3x decrease in insertion time of space materials
Deployable & Inflatable Structures	Rigidizable Tubes	3m inflatable reflector ground demo	25m inflatable reflector ground demo	ISSEC Testbed Developed	•3x decrease in package volume; 4x increase in aperture size
Structural Dynamics & Geometry Control	Advanced Actuation Materials Characterization	Deployable Photon Collector Microlurch Testbed cryogenic step-hold actuator	Controlled Flexible Reflector Panel Testbed	3X displacement, 5x less power actuation	
Space Environmental Effects	2nd-Phase SEE NRA	Space Science NRA Electronics Test Bed on STRV1 c/d	Electrically-conductive Thermal Control Coatings Spacecraft Charging Guidelines	EMI Characterization	5x increase in operational-life of space materials

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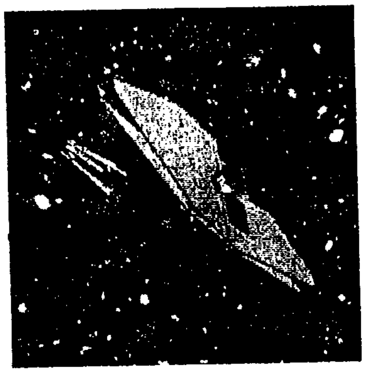
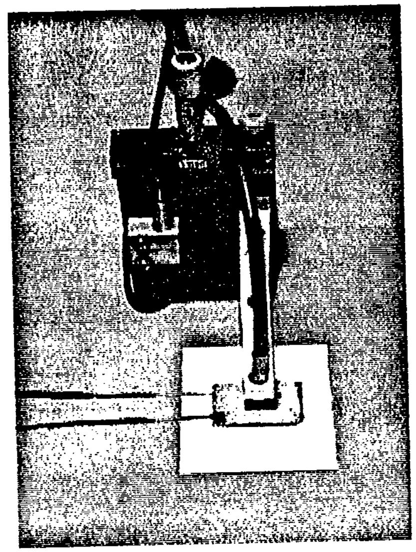
Structural Dynamics & Geometry Control



Next Generation Space Telescope



THUNDER Long-Stroke Actuator

Applications for Future Space Missions:
Low-cost, lightweight structures with integrated efficient actuation and controls for on-orbit correction of geometry errors and changes and suppression of dynamic response

Applications for Ground:
Smart structures that adapt to changing environmental conditions for aircraft, buildings, bridges

Objectives:
- Cryogenic and high temperature actuator capability
- 10x improved dynamic actuator life and efficiency
- Efficient, affordable long-stroke actuators for instrument scanning, optical positioning, interferometer delay lines

Approach:
- Develop efficient motorless actuators for positioning and motion suppression in extreme environments
- Develop system level methods for vibration suppression and precision pointing when using flexible components
- Validate on focus testbeds

Deliverables & Schedule:
- Complete characterization of THUNDER & Rainbow actuator concepts — Q2 98
- Demonstrate cryogenic position-hold actuators — Q1 99

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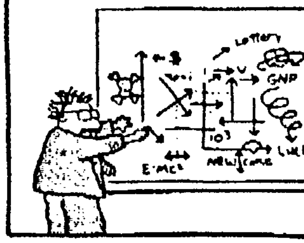
Joint Planning Team



Relevant Power Technologies

- Thermophotovoltaics
- Photovoltaics
- Li-ion Batteries
- Fuel Cells
- Free Piston Stirling Engines
- Power Management and Distribution

RJS98-001.5

Spacecraft System Power Technology Program

Major Milestones

FY	1997	1998	1999	2000	2001	2002	2003
PHOTOVOLTAICS	MBG CONC. NMP HDW. DELIVERED 2.7 kW 80 W/kg *	COMM'L >24% MBG CELLS, 3 x 7cm *; UPDATE RADIATION HANDBOOK; VERIFY HI VOLT DESIGN	UNIV RAD DAMAGE MDL COMP; 30% MBG CELL *	DEMO 20% T/F CELL; 300 W/kg ARRAY >300 W/m² *	$300/W ARRAY; DEMO HI-VOLT IM² MODULE		
ENVIRONMENTAL EFFECTS	EWB 5.0; PATHFINDER LANDING	NASCAP/LEO UPGRADE	ISS PC LAUNCH	NASCAP/GEO UPGRADE	MOON, GEO EWB		
CHEMICAL STORAGE	100 W-hr/kg 10 YEAR LEO BATTERY DESIGN CPV NiH_2; Li-ION BATTERY DESIGN FOR TRANSFER TO FLIGHT @ 100 Wh/kg	* Li-ION SOLID POLYMER BATTERY; DEMO LOW TEMP Li-ION FOR MARS PROGRAM	BIPOLAR NiMH 100 W-hr/kg 2x SOA 1/2 VOLUME 20 YEAR GEO DESIGN	2X SOA 100 W-hr/kg CPV NiH_2 BATTERY 10 YEAR LEO	BIPOLAR NiMH 100 W-hr/kg 2x SOA 1/2 VOLUME 20 YEAR GEO BATTERY		* SPACE PROTOTYPE Li-ION, 150 W-hr/kg 2-4x SOA, 250 W-hr/ℓ 1/2 SOA COST 2000 CYCLE LIFE
MECHANICAL STORAGE FLYWHEELS	* ADV. TECH COMP.; LEO FES LAB SYSTEM (44 Whr/kg)	PROTOTYPE IPACS (37 Whr/kg) *	10x SOA W/kg SYSTEM - LONG LIFE	GEO BENCH MODEL (88 Whr/kg)			2nd GEO BENCH MODEL (120 Whr/kg)
POWER MANAGEMENT, DISTRIBUTION	INITIAL MODULAR TESTBED COMPLETE *; ISUS PMAD DEMO	HIGH POWER PEBB TEST-BED; LOW POWER PEBB TEST-BED; ADV. PRKE	BRASSBOARD POWER DIST. UNIT; HI DENSITY WIDE TEMP 25°C - 300°C NO RHU's *	AUTONOMOUS MODULAR SYSTEM TEST-BED; PEBB BASED PMAD DEMO			
RADIOISOTOPE CONVERSION ADVANCED SYSTEMS	* >20% EFF TECH. SELECTION 3-5 x LESS Pu; DEMO POWER DEVICE/DIAMOND/TE COOLER FOR THERMAL MANAGEMENT	20% EFF. PROTOTYPE OPERATION					
POWER MATERIALS	DEMO LOW TEMP POWER SUPPLY	DEMO DURABIL. OF HST SM3 THERM CONT. MATL.		DEMO ELECTRO-CHROMIC RADIATOR	DEMO 3X REDUCTION IN SOLAR ARRAY BLANKET MASS		

UNIQUE FACILITIES - ALL REQUIRED FACILITIES EXIST (WILL SUPPLY LIST IF REQUIRED)

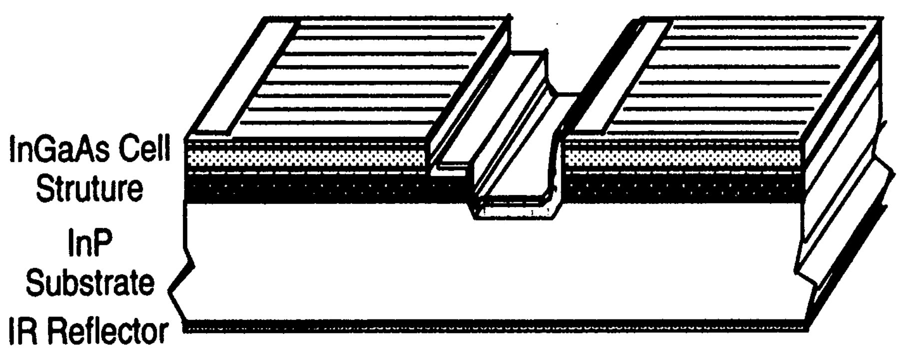
* INDICATES JOINT, CO-OPERATIVE PROGRAM, FUNDING LEVERAGE

RJS97-014.6

Photovoltaic Conversion Technology

FY 97 Accomplishments

Technology Development of Low Bandgap Solar Cell for Thermophotovoltaic Energy Conversion



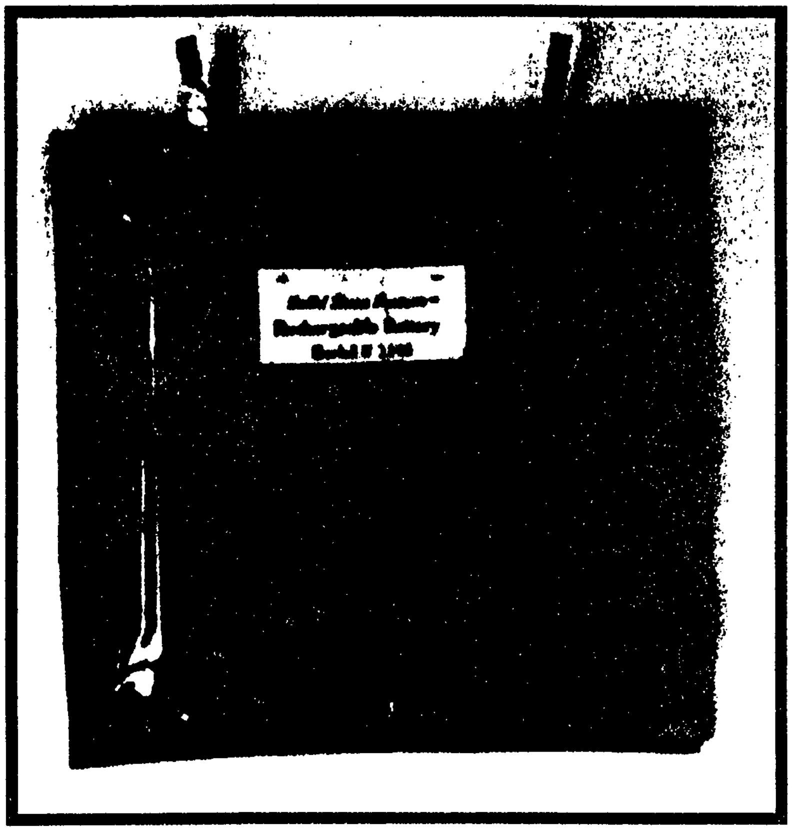
MIM device structure showing two series interconnected InGaAs cells.

- Monolithically Interconnected Module (MIM) InGaAs cell developed.
- Provides 2x increase in deep space power system efficiency.
- Device technology transferred to a small, woman-owned business, who is currently under contract with Bettis Atomic Power Laboratory to develop the MIM device.

NASA space technology transferred to major aerospace corporation (Westinghouse) for multi-million dollar development effort.

Spacecraft Systems Power Technology

Technology Development of Dual Use Rechargeable Lithium-Ion Polymer Batteries



- **Cooperative TRP effort very successful**
  - Progress made toward replacement of NiCd batteries for Military and space users
- **Major performance and manufacturing advances achieved for dual-use applications**
  - Demonstrated 3x specific energy of SOA NiCd toward target of 200 Whr/kg (6x NiCd)
  - Automated production capability and development
- **Penetration of markets for laptop computers, portable military applications and NASA missions is imminent**
- **Combination of in-house, industry, university (CSP) and SBIR efforts being pursued to extend life, increase energy density and power density of lithium-ion solid polymer battery**

Battery cells and cell packs currently being tested by commercial, military and NASA end users

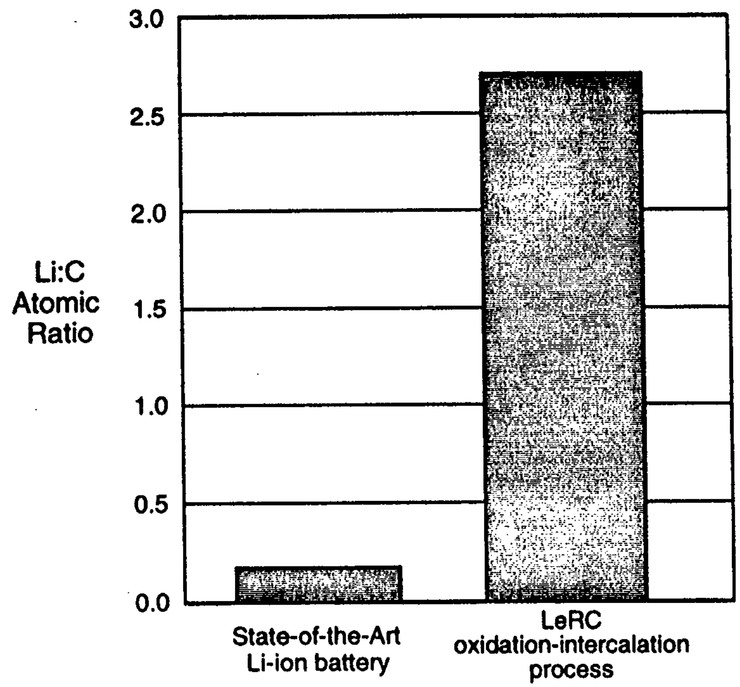
HB-6/97-4

Spacecraft Systems Power Technology Program

FY'97 ACCOMPLISHMENT

High Capacity, Light Weight Lithium-Ion Battery

State-of-the-Art Lithium-Ion Battery (0.17)
vs.
LeRC Oxidation-Intercalation Process (2.7)

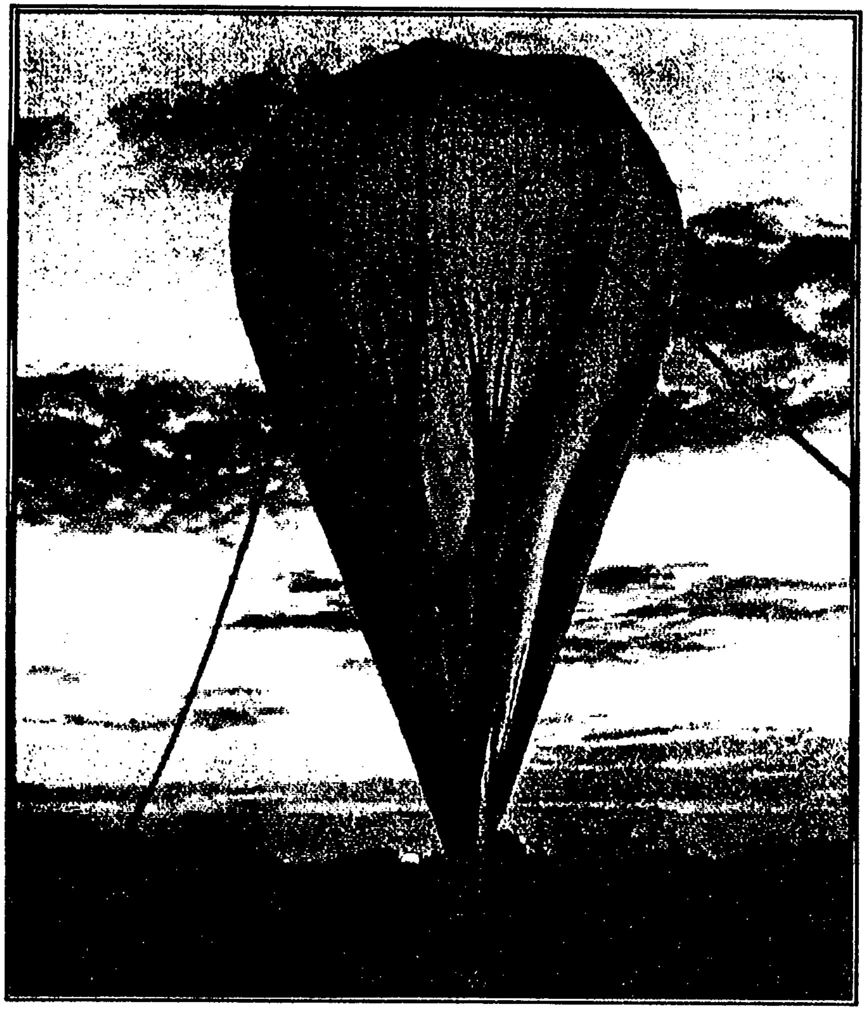


- Developed oxidation-intercalation techniques to produce lithium-ion battery anodes with greater than 6x state-of-the-art lithium to carbon concentrations
- High Li:C ratio means high power density unit mass for the batteries
- Identified high performance carbon precursor materials
- Optimized anode synthesis process to minimize cost and maintain performance

The demonstrated high Li:C atomic ratio anodes are necessary for high power density lithium-ion batteries

FY '97 FUEL CELL ACCOMPLISHMENTS

Hydrogen / Oxygen Fuel Cell Power System for Scientific Balloons



- Will demonstrate operation of a 200 W hydrogen / oxygen PEM fuel cell power system for use on scientific balloons
- Preliminary testing of the fuel cell has verified performance
- Testing of the complete fuel cell power system in the SMIRF facility has been completed successfully
- Flight test of power system scheduled for Spring '98

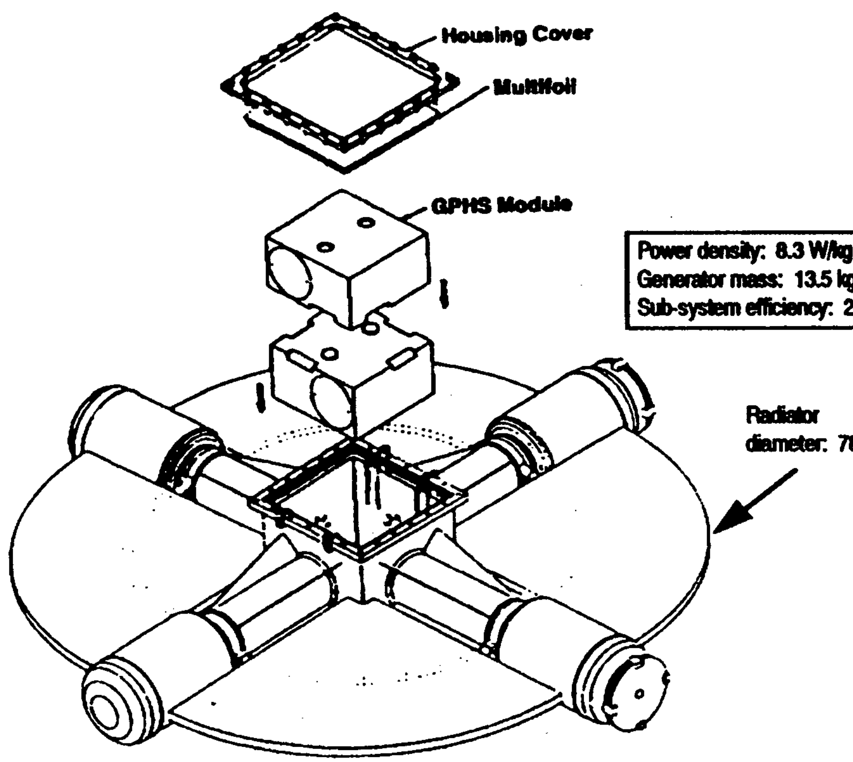
LeRC

MW97-004.6

Spacecraft Systems Power Technology Program

FY97 Accomplishments

Advanced Radioisotope Power Source



Power density: 8.3 W/kg
Generator mass: 13.5 kg
Sub-system efficiency: 24%

4 of 38 We Stirling Power Converters

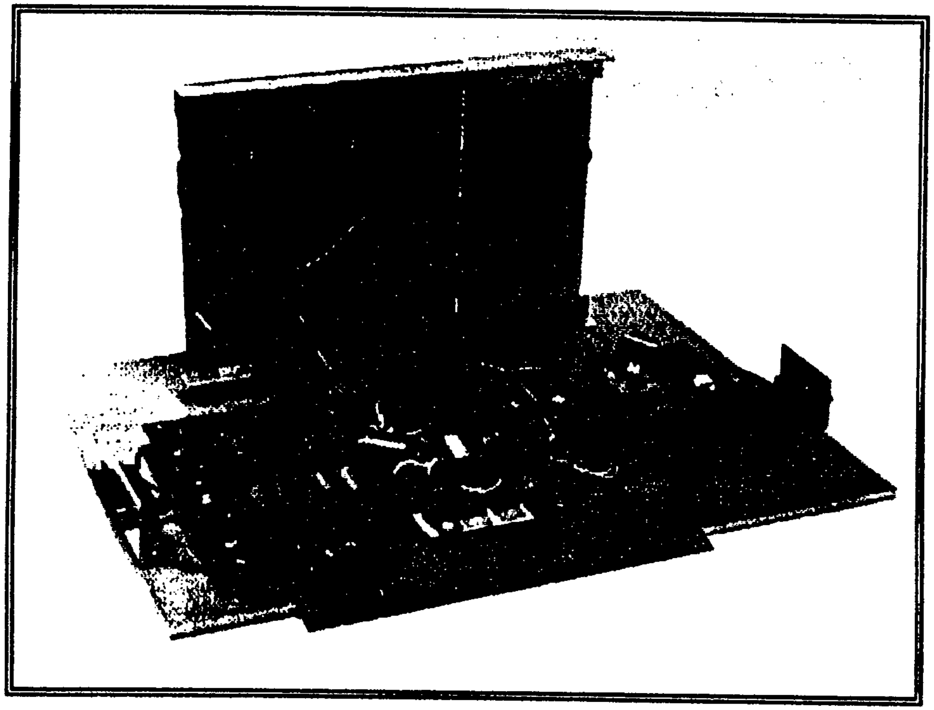
- **Completed two conceptual flight Stirling generator designs**
  - Al Schock (OSC) design above

- **Stirling chosen as back-up power system to AMTEC**
  - DOE Initiating sole source contract w/STC for brassboard
- **36 We RSG Phase 1 SBIR (NASA) awarded STC 3/17/97**
  - Design initiated
- **Similar 10 We radioisotope Stirling converter (RSG) has operated 32,500 hours (3/19/97) (3.7 years) without maintenance nor failure nor degradation with time**
- **All power converter component technologies are tested except for hermetic sealing, and the dynamic balancer**
  - Flexures tested @ 65% overstroke for 3.7 years No Failures
  - Alternators tested for 3.7 years No Failures
- **7 of 10 We RSG's ready for field tests (3 electrically heated, 4 to be fueled)**
- **350 We RSG's to be tested in '97 to determine vibration control and mitigation**
  - 3 on test in Europe
  - 2 STC/LeRC units fab'd/test 5/97

OMB97-JED.1.2

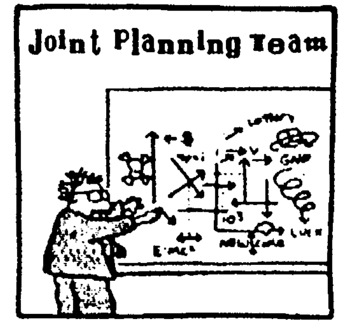
Power Management and Distribution

FY 97 Accomplishments



- **Developed a low power test-bed for Power Electronic Building Blocks (PEBB's)**
  - 30 Watts
  - 28 to 3.1Volt Converter
  - 85% Conversion efficiency
  - SEU tolerant
- **Provides capability for identifying PEBB requirements, modular component requirements, and evaluating controls and redundancy schemes**

Concluding Remarks



- **NASA has a relatively small but aggressive Spacecraft System Technology Program**
  - Responsive to USER needs
- **Many Joint Programs with DOD**
  - USAF, ARPA, BMDO
- **Key technologies relevant to ARO needs**
  - This meeting
- **Willing to work with you**
  - Help
- **A E Y W T K**

"RUDIMENTARY PHYSICS OF MAN-POWERED SYSTEMS"

Dr. Arthur Ballato

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Rudimentary Physics of Man-Powered Systems

Arthur Ballato

US Army Communications-Electronics Command
Fort Monmouth, NJ 07703

Synopsis

The most efficient production and transfer of power in systems takes place when the source impedance is matched to the load. For man-powered systems, this match is complicated by a number of factors. Indeed, for the class of problems encountered in man-powered systems, not only should the impedances (F/v) be matched, but also the elastances (F/x). In general, this is not possible, and compromises must be made. The situation is akin to that of needing to match both Reynolds and Froude numbers in certain fluid mechanics design problems. Part of the matching problem is the fact that humans are 'soft,' while most transducer materials are 'hard.' A rudimentary discussion of the physics/physiology involved is given, and an approach sketched for improvements.

Because of the mismatches in the ratios (F/x) and (F/v) for the man/machine interface that exist at the macroscopic level (one man and, e.g., one spring), the problem might have a more satisfactory resolution at the microscopic level. At present, the situation is much the same as obtained in 1947 with respect to the transistor. One such device was relatively large, and largely worthless. It was only with the advent of the IC and increasingly greater packing densities that the importance and utility of such devices grew. At present we are at the 'one transistor' level. At the microscopic level, the mechanical impedances and elastances of materials such as film piezoelectrics are more favorable for matching to the human. When coupled with distributed active circuitry for 'piezo-power-pixel' generation, accumulation, and management, the very act of wearing clothing in everyday activities can lead to the production of useful electrical output without the human-factors difficulties associated with wearing constricting apparatus or performing tiresome repetitive motions.

COMMENTS TO VuGRAPHS

01. Title: The title of this talk is "Rudimentary Physics of Man-Powered Systems." We start with an enormously expanded view of things, and then focus down on our subject. This is done to make a point: simple physical considerations, to be touched on later, indicate that the present-day approach to the soldier-power problem operates, in many respects, on the wrong scale. The proper scale for the problem of matching the impedance and elastance of a human to energy production components must be addressed. In the early years of this century, a child prodigy expressed her understanding of the world in the words: "Pipes are steel, but bones are real." In a real sense our job is to elucidate and maximize the coupling between these domains.

02. Limits of distance and mass in the universe [5]. Man's position is seen to be reasonably centrally located between the extremes.

03. Quantum-Gravity (Planck) Units [12]. These units are comprised of combinations of the natural constants $\hbar$ (Planck's constant), c (the speed of light), and G (Newton's gravitational constant). One can also add to this list the Planck force, $F = G\,(m_{P\ell})^2 / (\ell_{P\ell})^2 = c^4 / G = P_{P\ell} / c = 1.20 \bullet 10^{44}$ N. All of these values are seen to be wildly disproportionate to the scale of man.

04. Energy / Power Comparisons. Man is located in a central position. The tank entry is for the Abrams (M1A1) 120 mm cannon. Additional entries: Diesel fuel, 38.4 MJ/ℓ and gasoline, 34.9 MJ/ℓ.

05. Limits on the size of terrestrial creatures [3].

06. Creatures large and small [3]. Our hero is seen just below the Baluchitherium (3).

07. Of the four basic forces, the strong and weak are too short range for our considerations. We lump inertia with gravity because of Einstein's Equivalence Postulate; the origin of inertia is unknown at a fundamental level. All other 'forces' are electromagnetic (EM) in origin. Man's everyday world is dominated by EM and gravitational fields. Reynolds number: ρ is the mass density, η is the viscosity coefficient, and ℓ is a length characteristic of the problem. Froude number: g is the local acceleration of gravity, ~ 9.81 m/s^2, and ℓ is a length characteristic of the problem. It is usual that simultaneous constraints on a problem, such as Re and Fr, cannot both be completely satisfied, and compromises must be made.

08. Reynolds number domain for certain creatures and man-made structures [8]. For submarines, the Mach number is normalized to the speed of sound in sea water, ~ 1,560 m/s.

09. The Froude number can be thought of as the ratio of centripetal to gravitational forces acting on an inverted pendulum [3]. When Fr ~ 1, walking breaks into running, when more leg-time is spent in the air.

10. Size-independent dimensionless groups in mammals [3]. Small allometric mass exponent means ~ independent of mass (αλλοιος = unlike).

11. Total weight lifted (press + snatch + clean-and-jerk) vs body weight [3]. This is a measure of maximum exertion; the slope of 2/3 is indicative of constancy of bone stress, i.e., is proportional to cross-sectional area.

12. Kleiber's Law [3]. Graphical illustrations are given in VuGraphs 13 and 14.

13. Mass-specific metabolic rate vs body mass [3]. The curve has the form $(W/kg)_{resting} \propto (M)^{-1/4}$ as predicted from Kleiber's Law. For a 75 kg man, the curve gives ~ 1.4 W/kg, and 105 W. The conversion from kilocalories to joules is: 1 kilocalorie = 1 kcal = 4, 186.8 J.

14. Heat production vs body mass for mammals [3]. The curve has the form $(MJ/day) \propto (W)_{resting} \propto (M)^{3/4}$ as predicted from Kleiber's Law. The metabolic rate has a slope of ~ ¾; by the principle of 'elastic similarity,' this is ∝ muscle cross-section, which is ∝ force. The intercept at 75 kg (man) gives ~ 115 watt.

15. Energy Cost of Lateral Locomotion [2, 3, 15]. VuGraph 16 has a slope of ~ -1/3 for terrestrial animals; this is not for running; for running, the slope is ~ 0.40.

16. Cost of transport vs body mass [3]. Various modalities have differing slopes. These are not for racing speeds; see VuGraph 15.

17. Where are we now? Having observed some of the physiological characteristics of man (and other creatures), this question points to comparisons of energy sources (including man), and the prospects for transduction from one form to another.

18. Conversion Efficiencies. Adapted from Table V.2, p. V.2 of [7]. We would like soldier-power conversion from mechanical to electrical to be as efficient as possible; the 99% figure listed is for very large commercial stations.

19. Energy storage by batteries and elastic springs compared. Also listed are some SUO requirements. It is interesting to note that if sleep is considered 'recharging one's batteries,' then man as a secondary battery is good for 25k recharges.

20. Rations [4, 13, 14]. The values given represent averages over an entire day (86,400 seconds). A resting man requires ~ 1 kcal/(kg-hour) ~ 1.16 W/kg. The figure can be twenty times this for an athlete in action, or ~ 23.3 W/kg; for a mass of 72.6 kg, this works out to ~ 1,700 W. The caloric demands are stated without regard for nutritional balance. The 'fuel mix' is very important; for example, if simply burned, then the energy

content (kcal/gm) of any fat is ~ 9; alcohol is ~ 7; any sugar is ~ 4. It would seem that this should be the order for deriving dietetic energy, but "fat burns in the flame of carbohydrates;" (one needs carbohydrates to metabolize fats). Therefore, one needs carbohydrates to burn fat energy into CO_2. Since most people have excess fat on the body, if one was forced to choose a single substance for energy during a mission, sugar would be appropriate; moreover, the brain runs on glucose. Alcohol represents 'false calories' in the sense that the efficiency of its energy transfer to ATP (the energy the body uses) is low, and actually requires some energy to turn into fat. [I am indebted to the following individuals at US Army Natick RDEC; Soldier Systems Command; and Research Institute of Environmental Medicine, Natick, MA for information supporting this VuGraph: Dr. Irwin Taub, Judy Aylward, Dr. Pat Dunn, Reed Hoyt, and Maureen Abbruzzese.]

Nutritional 'calories' are kilocalories; the numerical factor for converting kilocalories to joules is: 1 kilocalorie = 1 kcal = 4, 186.8 J. A useful rule-of-thumb for converting kcal/day to watt is: 2,000 kcal/day ~ 100 W. By comparison, the sun radiates ~ $3.9 \bullet 10^{26}$ W, so the flux incident on the Earth is ~ $1.4 \bullet 10^{3}$ W/m^2 ; at the surface it is ~ $1.0 \bullet 10^{3}$ W/m^2, or only about 10 times the heat production of a resting human (see the caption to VuGraph 37).

21. Heckmann Diagram [11]. Phenomenological couplings between the intensive and extensive variables of the electrical, mechanical, and thermal fields. The effects noted on the diagram can be used for soldier-powered devices; the piezoelectric effect is particularly apt because of the direct conversion of mechanical to electrical energy.

22. The 32 crystallographic point groups; the acentric groups are piezoelectric, with the exception of group 432.

23. Linear elastopiezodielectric constitutive equations. These are generalized versions of Hooke's Law: stress is proportional to strain; in the piezoelectric case, one adds a term to represent the electric force. This effect is apt for use in soldier-powered systems because of the direct nature of the transduction mechanism.

24. Piezoelectric Coupling Coefficients. These are dimensionless measures of the efficacy of transduction of energy from mechanical to electrical or vice-versa.

25. Comparison of Ceramic Actuator Technologies. For some of the newer materials and configurations (such as functionally gradient materials), piezoelectric strain can be substantial.

26. Electrical & Mechanical Variables. In dealing with soldier-generated power, the quantities V, Q, I, F, x, and v must be dealt with; the familiar products, energy and power, are often quoted as specifications. The quotients, elastance and impedance, have just as often not been adequately dealt with. Just as with Re and Fr (VuGraph 7), it is usually not possible to satisfy both constraints simultaneously, particularly in the time-varying case.

27. Matching. An example of the impedance/elastance matching problem is the fact that it is more tiring to split logs with a small hatchet than with a large ax; the hatchet requires a greater impact speed, and the kinetic energy that must be given to the arms results in a greater rate of fatigue.

28. Man as Seen by .... The big picture, given in earlier VuGraphs, starts with the cosmologist; the physiologist deals with the man as a macroscopic energy producer. The atomic picture of the physicist and chemist is too small. At the level of the biologist ... cells, the impedance and elastance levels are more appropriate to generation of casual soldier power.

29. Man-Sized Units. Compare with VuGraph 3; the corresponding force levels are $F = P / v = 10^{-1}$ to 10^{2} N (roughly 10 gram to 10 kg mass equivalent). Impedance and elastance levels should be commensurate when attempting to match between the human and a device, be it piezoelectric or any other type.

30. Volume vs number of cell types; a 75 kg man (with ~ the density of water) has a volume of $\sim 7.5 \bullet 10^{4}\,\mathrm{cm}^{3}$ and $\sim 10^{13}$ cells.

31. Cells. Cell size is midway between man considered as an individual and as an aggregation of atoms. We are at the analogous stage of development that the transistor was in 1947; single transistors, by themselves, are not very useful; their utility comes from aggregation.

32. Summary. This is actually a summary of what future developments might be like, given proper development of the ideas sketched here. One must differentiate between 'deliberate' power generation, where, e.g., a soldier turns a crank attached to an electric generator, and 'casual' power generation, where, e.g., the clothing, is capable of generating power when subjected to arbitrary movements. These may be walking, gesturing, or any movements. For this to be possible, the material is 'smart,' and can sense the type of movement (how the deformation is occurring), can actively switch the individual pixels in polarity and topology (series/parallel, etc.) to balance dynamically by impedance/elastance changes in order to accommodate the demands for energy/power storage, distribution, and use. 'Active matrix' display panels, with a transistor at each pixel, is indicative of what can be done. With the power requirements of mobile (man-portable) communications systems dropping at the dramatic current rates (reminiscent of Moore's Law), it is projected that the soldier may well have his communications needs met in the future by a steady-state power requirement of 5 watt, or less; this should be well within the capability of a soldier-powered configuration for power harvesting.

33. References.

34. References (continued).

35. References (continued).

36. Appendix 1. Dimensional formulas [3].

37. Appendix 2. Body surface vs body mass [3]. Area is $\propto$ (volume)$^{2/3}$ $\propto$ (mass)$^{2/3}$; the slope of the curve is 2/3. For a man of ~ 75 kg, the area is ~ 1.5 m^2 ; if heat production is 150 watt, then the flux is 100 W/m^2 . This is 10% of the incident heat flux from the sun at the Earth's surface (see the caption to VuGraph 20), and might lead one to conclude that a sizable portion of this heat could be made available for conversion to electric energy. One problem with usage of body heat is its quality, viz., the spectral distribution as a 'blackbody' radiator (T = 37° C, versus ~ 5,500° C for the sun), another is the inefficiency of conversion using transport phenomena (conduction); still another is the threat of departure from homeostasis, quite apart from psychological considerations.

38. Appendix 3. Oxygen consumption vs body mass [3], for guinea pigs. The slope of ~ 2/3 is $\propto$ lung area.

Prospector IX Workshop:
Human Powered Systems and Technologies
Durham, N.C.
3 November 1997

Rudimentary Physics of Man-Powered Systems

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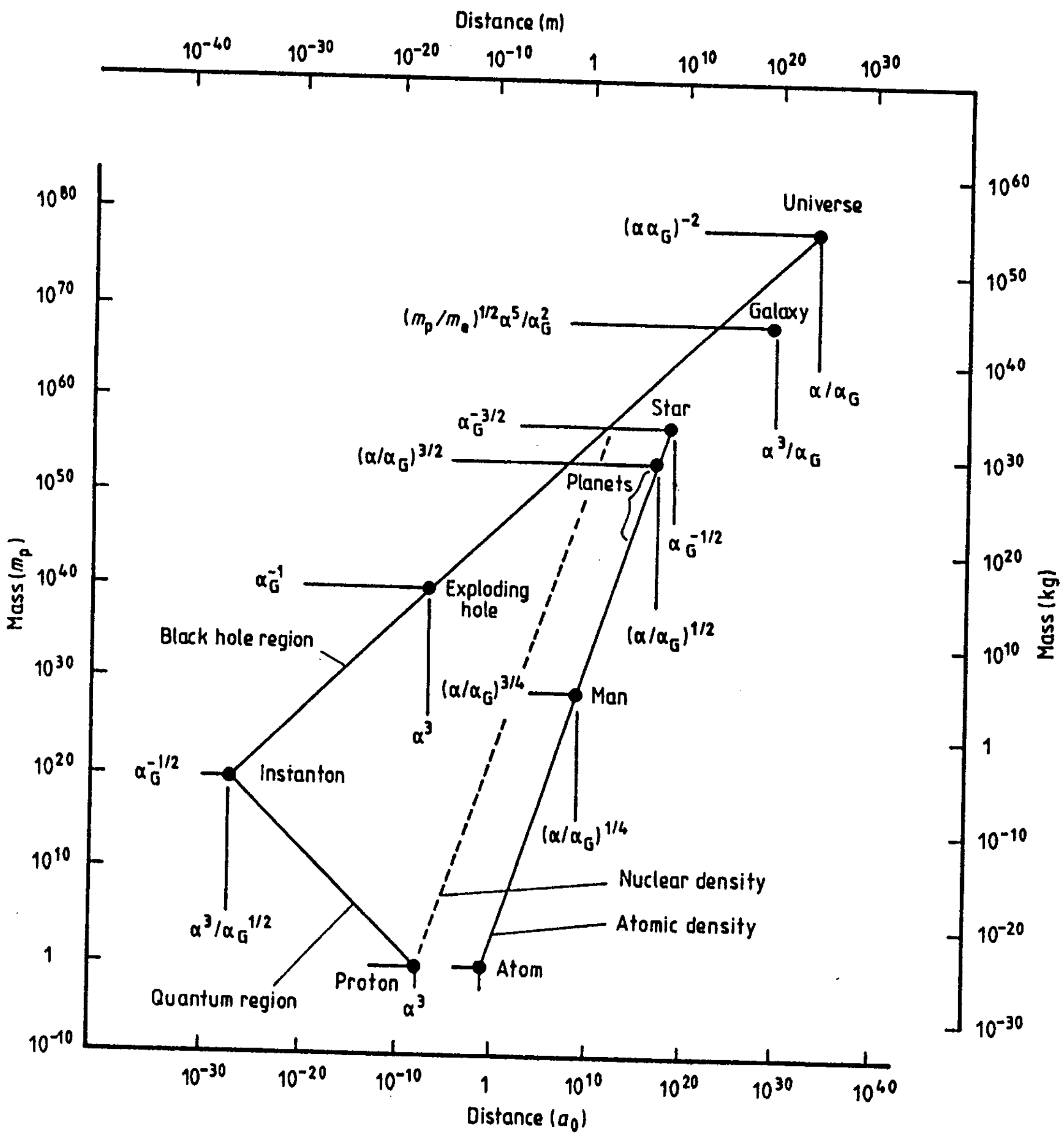

Distance (m)
10^{-40} 10^{-30} 10^{-20} 10^{-10} 1 10^{10} 10^{20} 10^{30}
Mass (m_p)
10^{80} 10^{70} 10^{60} 10^{50} 10^{40} 10^{30} 10^{20} 10^{10} 1 10^{-10}
Mass (kg)
10^{60} 10^{50} 10^{40} 10^{30} 10^{20} 10^{10} 1 10^{-10} 10^{-20} 10^{-30}
Distance (a_0)
10^{-30} 10^{-20} 10^{-10} 1 10^{10} 10^{20} 10^{30} 10^{40}
Universe
$(\alpha\alpha_G)^{-2}$
α/α_G
Galaxy
$(m_p/m_e)^{1/2}\alpha^5/\alpha_G^2$
α^3/α_G
Star
$\alpha_G^{-3/2}$
$\alpha_G^{-1/2}$
Planets
$(\alpha/\alpha_G)^{3/2}$
$(\alpha/\alpha_G)^{1/2}$
Exploding hole
α_G^{-1}
α^3
Black hole region
Man
$(\alpha/\alpha_G)^{3/4}$
$(\alpha/\alpha_G)^{1/4}$
Instanton
$\alpha_G^{-1/2}$
$\alpha^3/\alpha_G^{1/2}$
Nuclear density
Atomic density
Quantum region
Proton
α^3
Atom

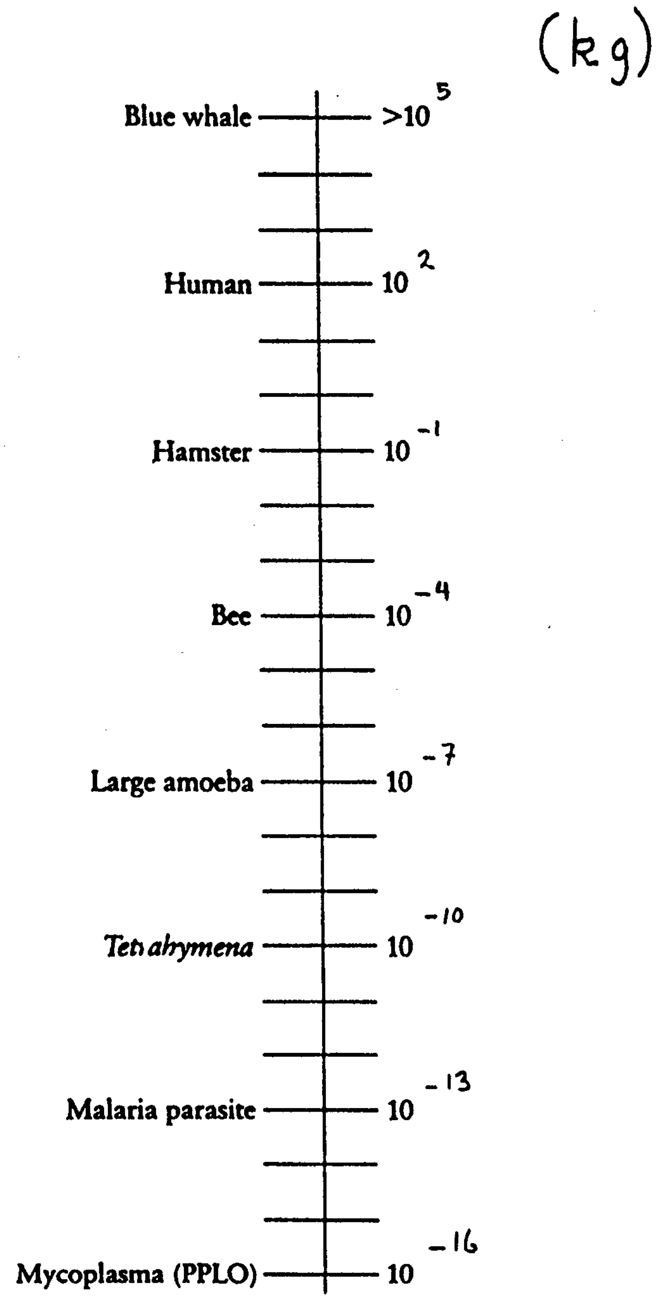
QUANTUM-GRAVITY (PLANCK) UNITS

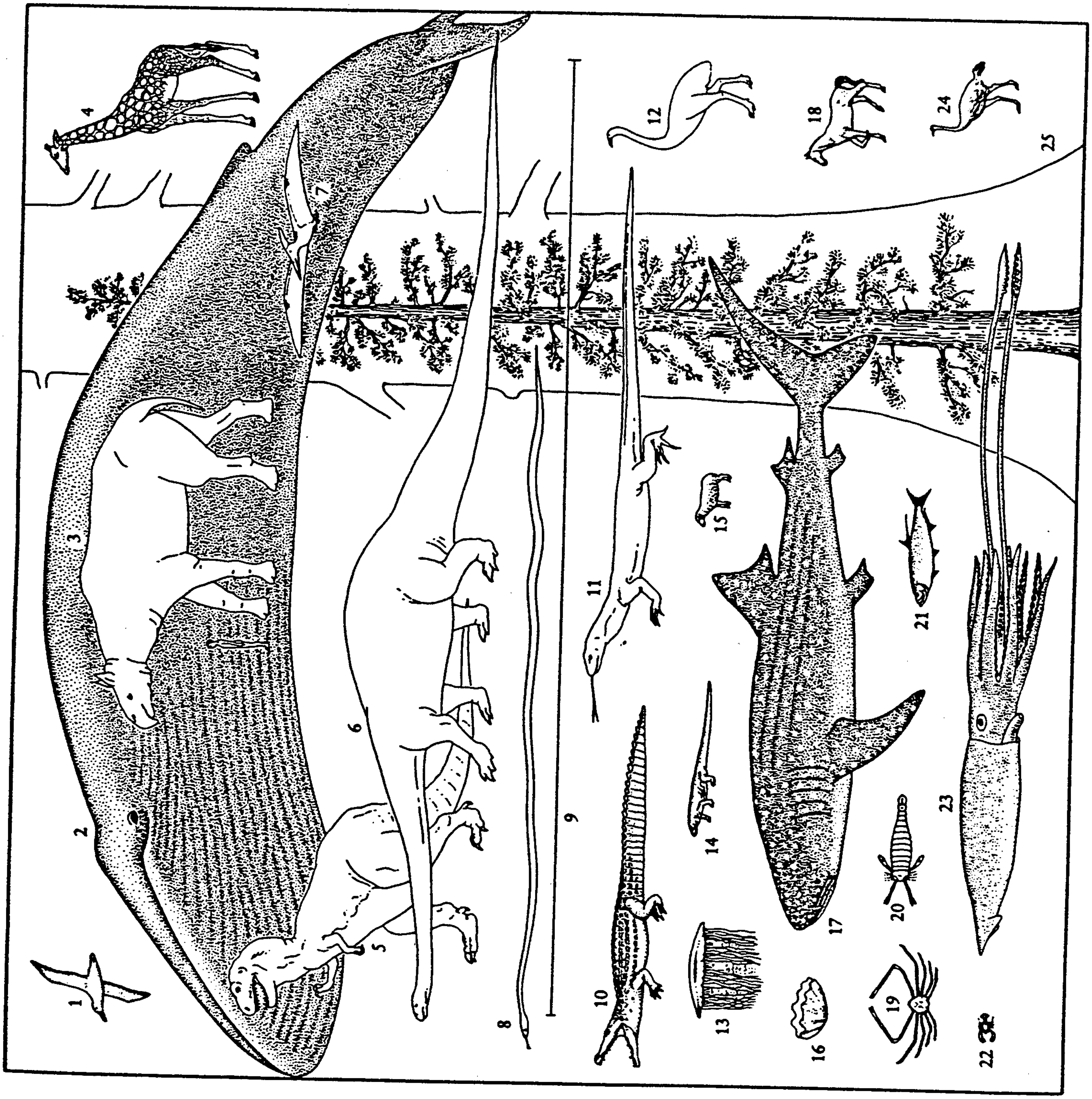
MASS	$m_{P\ell} = (\hbar\, c / G)^{1/2}$	$2.177 \bullet 10^{-8}$ kg
LENGTH	$\ell_{P\ell} = (\hbar\, G / c^3)^{1/2}$	$1.616 \bullet 10^{-35}$ m
TIME	$t_{P\ell} = (\hbar\, G / c^5)^{1/2}$	$5.391 \bullet 10^{-44}$ s
ENERGY	$E_{P\ell} = (\hbar\, c^5 / G)^{1/2}$	$1.956 \bullet 10^{9}$ J
VELOCITY	$v_{P\ell} = c$	$2.998 \bullet 10^{8}$ m/s
POWER	$P_{P\ell} = (c^5 / G)$	$3.628 \bullet 10^{52}$ W

ENERGY / POWER COMPARISONS

- H transition (1420 MHz) $E = 9.4 \bullet 10^{-25}$ J/photon
- Human $P = 10 - 1000$ W
- Automobile engine $P = 72$ kW input; 9 kW output
- Tank cannon $E = 40$ MJ input; 11.4 MJ output
- US Power grid $P = 400$ GW @ 60 Hz
  $E = 6.7$ GJ per cycle
- Pulsars $P = 2 \bullet 10^{29}$ to $5 \bullet 10^{31}$ W @ 200 Hz
  $E = 2.5 \bullet 10^{29}$ J per cycle (10^{20} US grids)

166


(kg)
Blue whale
>10^5
Human
10^2
Hamster
10^-1
Bee
10^-4
Large amoeba
10^-7
Tetrahymena
10^-10
Malaria parasite
10^-13
Mycoplasma (PPLO)
10^-16


1
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20
21
22
23
24
25

Forces:

- [weak, strong]
- gravity/inertia
- electromagnetic: viscosity, friction, cohesion, surface tension, elasticity, etc.

Large creatures: gravity dominates

Small creatures: viscosity, surface tension, … dominate (EM)

- Ant can support many ants; a horse can't support the weight of another horse
- Ants can fall from trees unhurt; men can't

Dimensionless numbers:

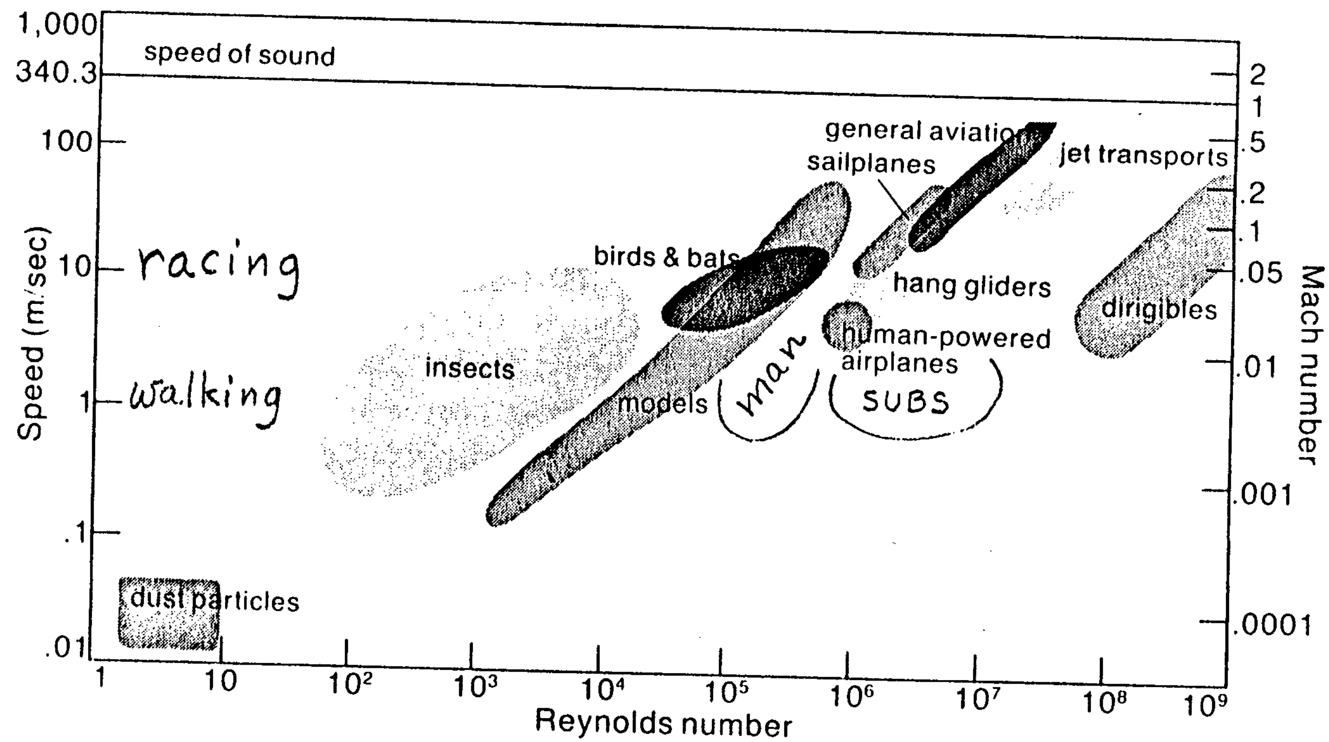
Reynolds number = Re = $\rho \bullet \ell \bullet v / \eta$

- Re is the ratio of inertia force to the viscous force on a fluid
- Re small: viscous forces dominate; flow smooth, sluggish; drag $\propto v$ (Stokes)
- Re large: inertial forces dominate; flow swift, often turbulent; drag $\propto v^2$

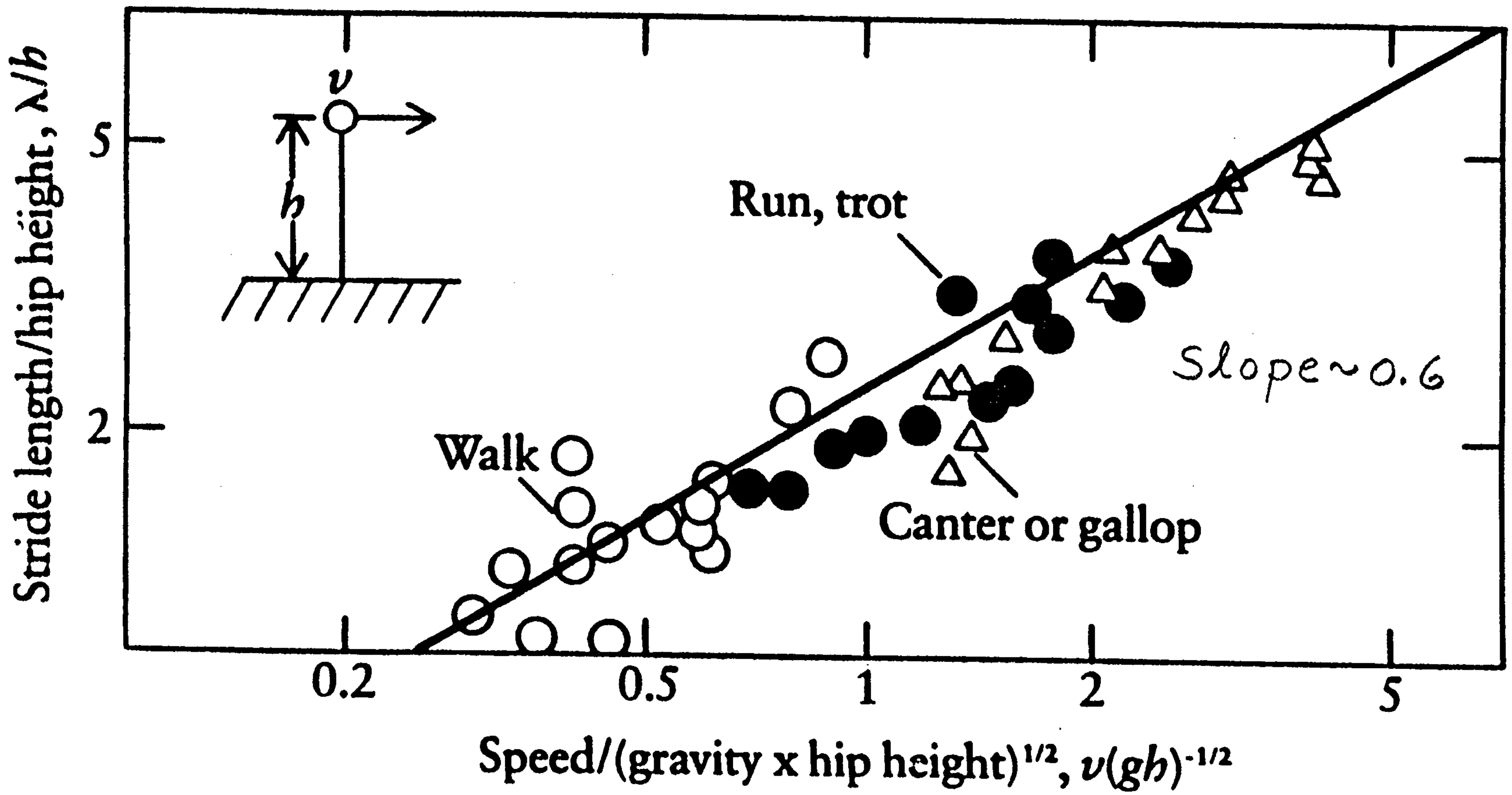
Froude number = Fr = $v^2 / g \ell$

- Fr is the ratio of inertia force to the gravity force on a fluid
- Fr small: gravitational forces dominate
- Fr large: inertial forces dominate

Reynolds number = inertial force / viscous force = $\rho \bullet v \bullet \ell / \eta$



American Scientist, Vol. 77, March-April 1989, p. 167.



$(\text{Froude number})^{1/2}$

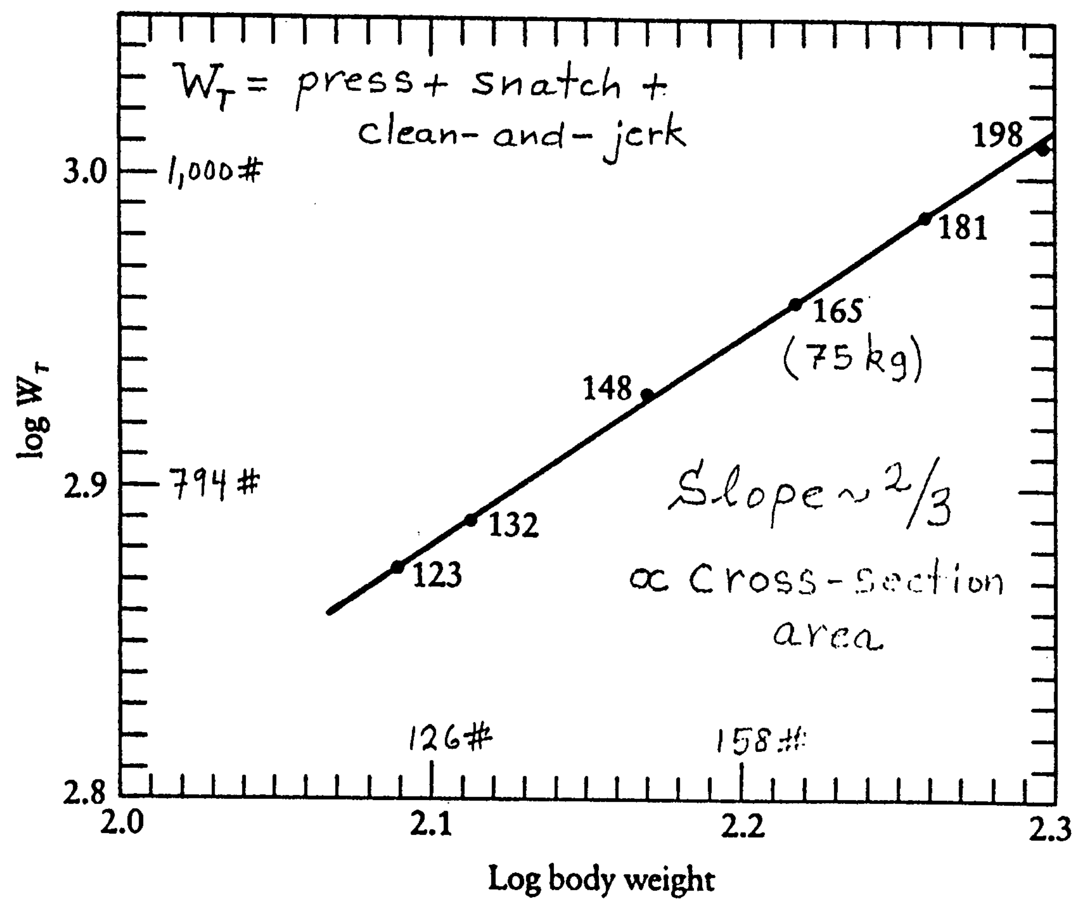
$$\left.\begin{array}{ll} \text{Centripetal}: & mv^2/h \\ \text{gravitational}: & mg \end{array}\right\} \quad \text{Ratio} = v^2/gh = \text{Froude}$$

Size-independent dimensionless groups in mammals.

Dimensionless group		Numerical value for an animal weighing 1 kilogram	Allometric mass exponent *
1. $\dfrac{\text{tidal volume}}{\text{breath time}} \Big/ \dfrac{\text{heart stroke volume}}{\text{pulse time}}$		2.0	0.00
2. $\dfrac{\text{mass of blood}}{\text{mass of heart}}$		8.3	0.01
3. $\dfrac{\text{velocity of pulses waves in the aorta}}{\text{velocity of blood in the aorta}}$		26.0	−0.05
4. $\dfrac{\text{pulse wavelength in the aorta}}{\text{length of the aorta}}$		8.7	−0.05
5. $\dfrac{\text{time for 50\% of growth}}{\text{lifespan in captivity}}$		0.03	0.05
6. $\dfrac{\text{gestation period}}{\text{lifespan in captivity}}$		0.015	0.05
7. $\dfrac{\text{respiratory cycle}}{\text{lifespan in captivity}}$		3.0×10^{-9}	0.06
8. $\dfrac{\text{cardiac cycle}}{\text{lifespan in captivity}}$	$(1.5 * 10^{9})^{-1} =$	6.8×10^{-10}	0.05
9. $\dfrac{\text{half-life of drug*}}{\text{lifespan in captivity}}$		0.95×10^{-5}	0.01

* Methotrexate.

* $\approx$ independent of mass



W_T = press + snatch + clean-and-jerk
1,000#
794#
126#
158#
198
181
165 (75 kg)
148
132
123
Slope ~ 2/3 ∝ Cross-section area
3.0
2.9
2.8
2.0
2.1
2.2
2.3
log W_T
Log body weight

KLEIBER'S LAW

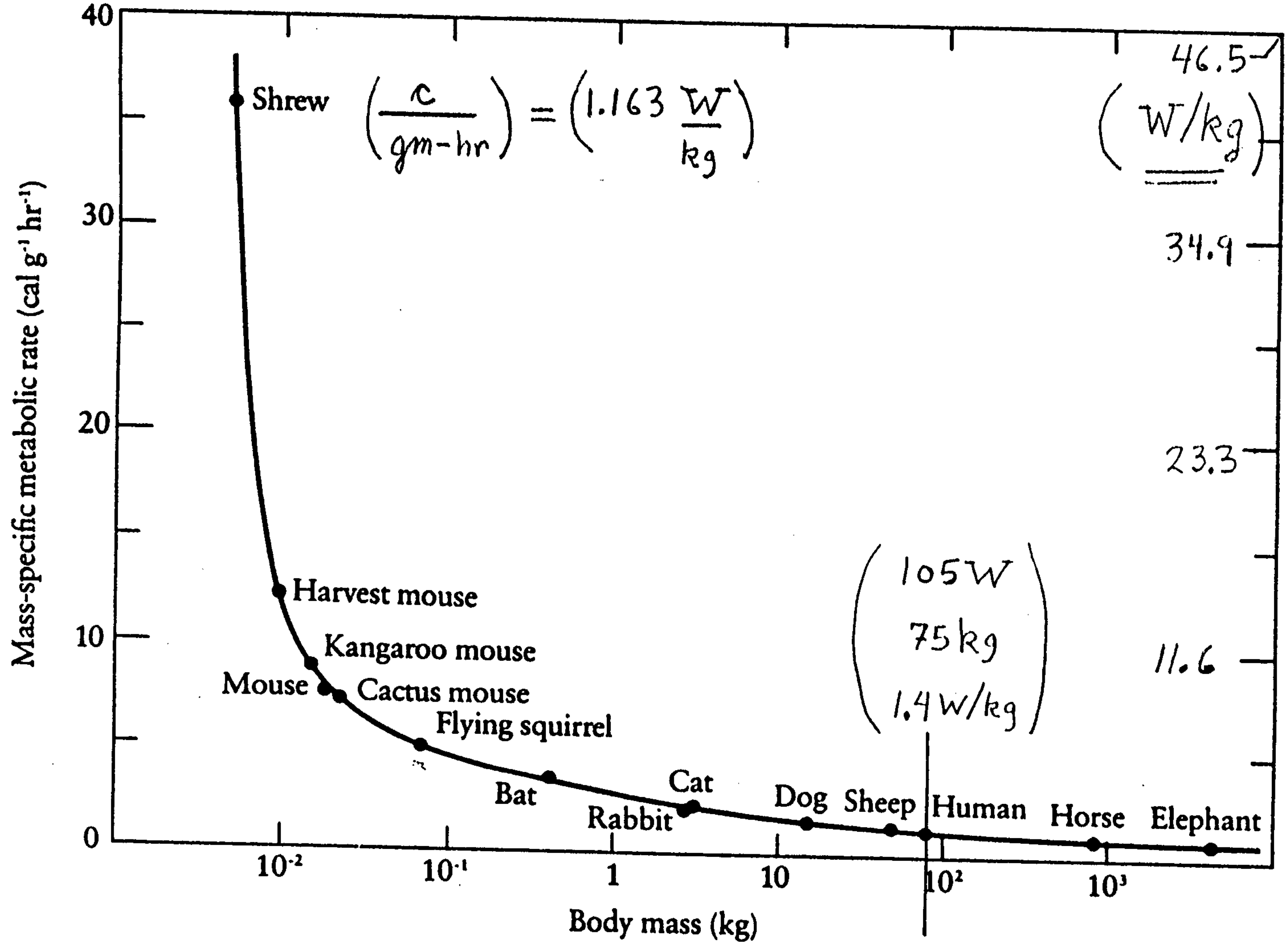
An animal's resting metabolic rate is proportional to $(\text{body mass})^{3/4}$

$$(\text{MJ/day}) \propto (\text{W})_{\text{resting}} \propto (\text{M})^{3/4}$$

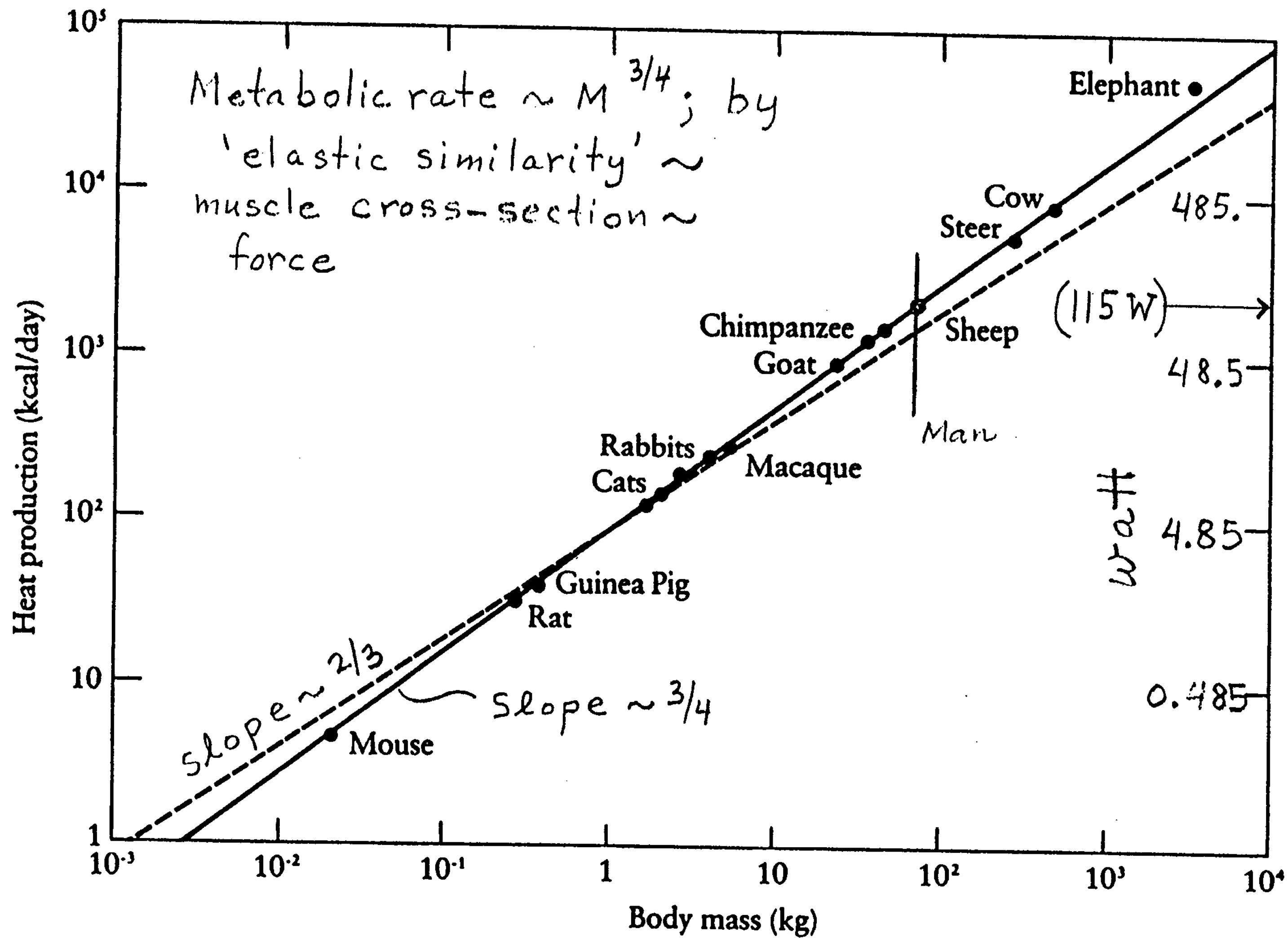
Therefore,

$$(\text{W/kg})_{\text{resting}} \propto (\text{M})^{-1/4}$$

Larger animals are metabolically more efficient.



Mass-specific metabolic rate (cal g⁻¹ hr⁻¹)
40
30
20
10
0
Shrew
Harvest mouse
Kangaroo mouse
Mouse
Cactus mouse
Flying squirrel
Bat
Rabbit
Cat
Dog
Sheep
Human
Horse
Elephant
10⁻²
10⁻¹
1
10
10²
10³
Body mass (kg)
(c / gm-hr) = (1.163 W/kg)
46.5
(W/kg)
34.9
23.3
11.6
105W
75kg
1.4W/kg


Metabolic rate ~ M 3/4 ; by
'elastic similarity' ~
muscle cross-section ~
force
Heat production (kcal/day)
Body mass (kg)
Elephant
Cow
Steer
Sheep
Chimpanzee
Goat
Macaque
Rabbits
Cats
Guinea Pig
Rat
Mouse
Man
slope ~ 2/3
slope ~ 3/4
(115 W)
485.
48.5
4.85
0.485
watt
10⁵
10⁴
10³
10²
10
1
10⁻³
10⁻²
10⁻¹
1
10
10²
10³
10⁴

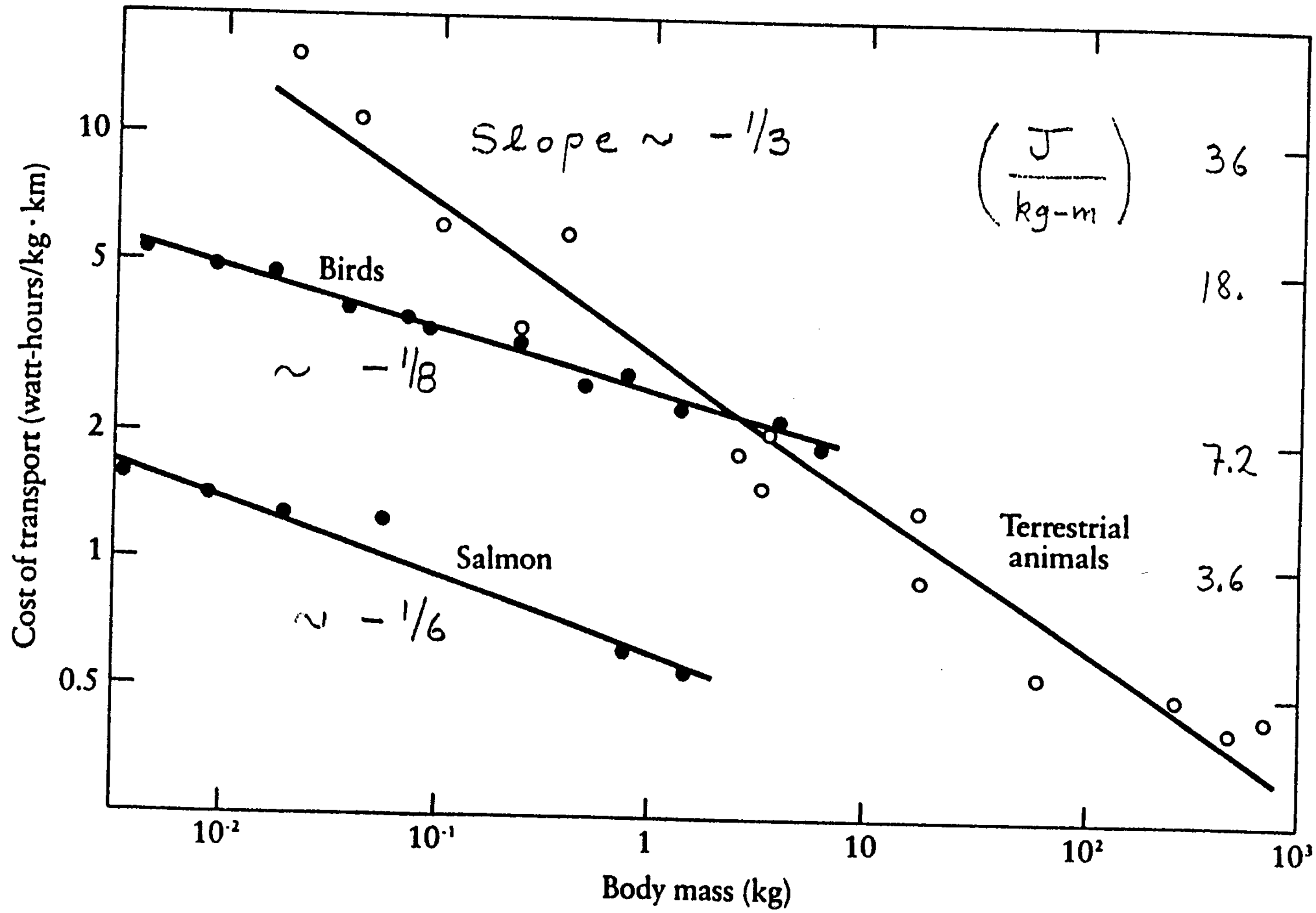
ENERGY COST OF LATERAL LOCOMOTION

Creatures: Energy Cost = Metabolic rate/speed (J/kg-m)

Running mammals: $E \sim 12.4 \bullet (\text{body mass})^{-0.40}$

Most of the energy goes into moving the limbs back and forth with respect to the body.

Helicopter	10 J/kg-m
Automobile	2
Man (72.6 kg)	2.2
Horse, Flyer (72.6 kg), Big jet	1
Swimmer (72.6 kg)	0.4
Long-distance freighter	0.1
Vertical (gravity)	9.81
Orbit (36MJ/kg; ht = 200 km)	<180>


Slope ~ -1/3
(J / kg-m)
36
18.
7.2
3.6
Birds
~ -1/8
Salmon
~ -1/6
Terrestrial animals
10
5
2
1
0.5
Cost of transport (watt-hours/kg · km)
10⁻²
10⁻¹
1
10
10²
10³
Body mass (kg)

WHERE ARE

WE NOW?

CONVERSION EFFICIENCIES

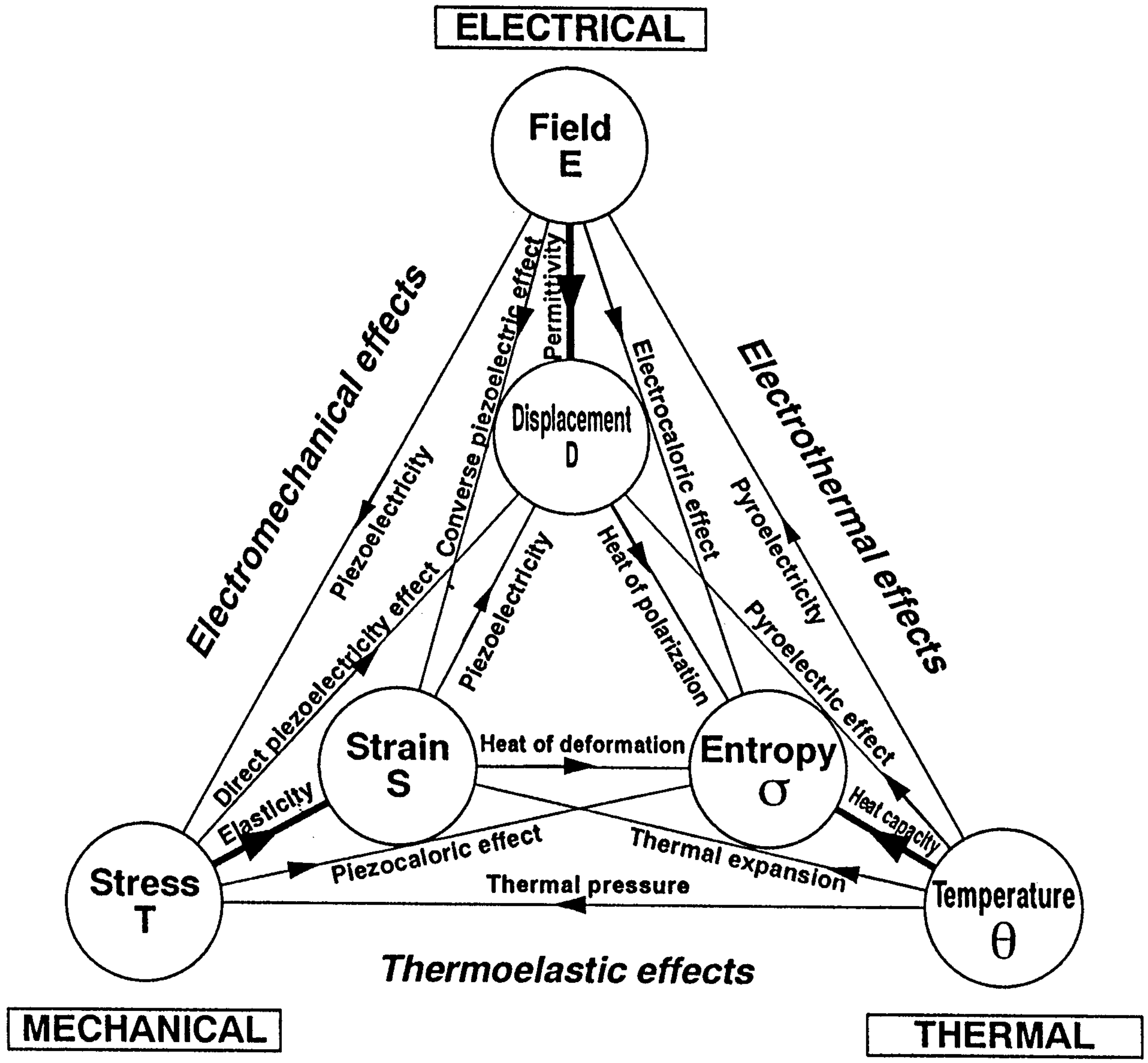
TO → FROM ↓	Mechanical	Electrical	Light	Chemical	Thermal
Mechanical	-	99% elec. gen.	-	-	100% brake drum
Electrical	93% elec. motor	-	40% gas laser	72% battery	100% heating coil
Light	-	27% solar cell	-	0.6% photosyn.	100% solar furnace
Chemical	45% muscle	91% dry cell	15% chem. laser	-	88% steam furnace
Thermal	47% steam turbine	7% thermocouple	3% light bulb	-	-

	BATTERIES				MECHANICAL SPRING
	Current SINCGARS		*Future*		
	Primary	Secondary	Primary	Secondary	
Energy Density (MJ/kg)	0.57 ($LiSO_2$)	0.18 (Ni-metal hydride)	1.3 ($Li/SOC1_2$)	0.4 (Li-ion)	0.013
Volumetric Energy Density (MJ/l)	0.65 ($LiSO_2$)	0.35 (Ni-metal hydride)	3 (Zn/air)	0.6 (Li-ion)	0.10

Existing SUO requirements	0 to 50 W on demand	<5W> for 30 days	10.8 MJ total

RATIONS

Conditions		kcal/day	watt
Normal temperatures	(T = 20°C to 30°C)		
• Operational	Normal	3,600	175
• Garrison	Normal	2,800	136
• Restricted	(≤ 10 days)	1,100 to 1,500	53 to 73
• Survival	(≤ 4 days)	400	19.4
Hot environment (T ≥ 30°C)	• Normal + 0.7% per kelvin above 30°C		
Cold environment (T ≤ 14°C)			
• Normal + 5% + 2 to 5% for extra clothing			
• Arctic		4,500 to 5,000	218 to 242
• Climb Mt. Everest (8,000 kcal/day; alternate climb/rest)		16,000	775
Tour de France		7,000	339
BMR	(1.17 W/kg)	1,640	80



BALLATO/030794/#10/SP

<table>
<tr><th rowspan="2">CRYSTAL SYSTEM</th><th rowspan="2" colspan="2">CENTRIC POINT GROUPS</th><th colspan="5">ACENTRIC POINT GROUPS</th><th rowspan="2">OPTIC AXES</th></tr>
<tr><th colspan="2">POLAR</th><th colspan="3">NONPOLAR</th></tr>
<tr><td>TRICLINIC</td><td colspan="2">$\bar{1}$</td><td colspan="2">1</td><td colspan="3">NONE</td><td rowspan="3">BIAXIAL</td></tr>
<tr><td>MONOCLINIC</td><td colspan="2">2/m</td><td>2</td><td>m</td><td colspan="3">NONE</td></tr>
<tr><td>ORTHORHOMBIC</td><td colspan="2">mmm</td><td colspan="2">mm2</td><td colspan="3">222</td></tr>
<tr><td>TETRAGONAL</td><td>4/m</td><td>4/m mm</td><td>4</td><td>4mm</td><td>$\bar{4}$</td><td>$\bar{4}2m$</td><td>422</td><td rowspan="3">UNIAXIAL</td></tr>
<tr><td>TRIGONAL</td><td>$\bar{3}$</td><td>$\bar{3}$ m</td><td>3</td><td>3m</td><td colspan="3">32</td></tr>
<tr><td>HEXAGONAL</td><td>6/m</td><td>6/m mm</td><td>6</td><td>6mm</td><td>$\bar{6}$</td><td>$\bar{6}m2$</td><td>622</td></tr>
<tr><td>CUBIC</td><td>m3</td><td>m3m</td><td colspan="2">NONE</td><td>23</td><td>$\bar{4}3m$</td><td>432</td><td>ISO-TROPIC</td></tr>
<tr><td></td><td colspan="2">11 GROUPS</td><td colspan="2">10 GROUPS</td><td colspan="3">11 GROUPS</td><td></td></tr>
</table>

GR623A/110593/#11/SP

LINEAR ELASTOPIEZODIELECTRIC CONSTITUTIVE EQUATIONS

$$T = c^E S - e E \qquad S = s^E T + d E$$
$$D = e S + \varepsilon^S E \qquad D = d T + \varepsilon^T E$$

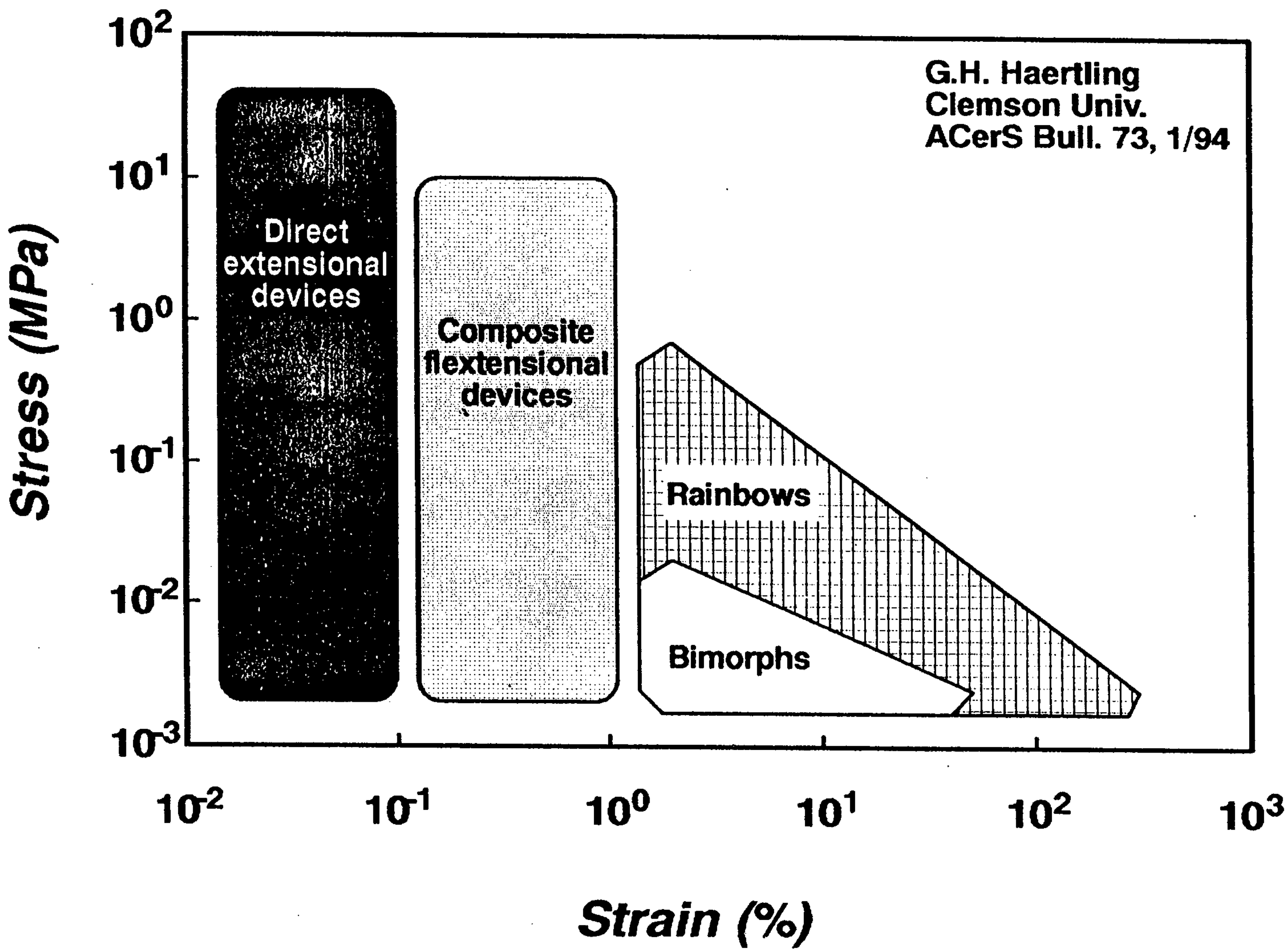
$$T = c^D S - h D \qquad S = s^D T + g D$$
$$E = - h S + \beta^S D \qquad E = - g T + \beta^T D$$

PIEZOELECTRIC COUPLING COEFFICIENTS, K

Generic forms for k^2:

$$k^2 = d^2/(\varepsilon\ s) = h^2/(\beta\ c) = e^2/(\varepsilon\ c) = g^2/(\beta\ s)$$

COMPARISON OF CERAMIC ACTUATOR TECHNOLOGIES



ELECTRICAL & MECHANICAL VARIABLES

QUANTITIES

voltage, V	force, F
charge, Q	displacement, x
current, $I = \partial Q/\partial t$	velocity, $v = \partial x/\partial t$

PRODUCTS

Energy = $V \bullet Q = F \bullet x$

Power = $V \bullet I = F \bullet v$

QUOTIENTS

Elastance = $V / Q = F / x$

Impedance = $V / I = F / v$

MATCHING

- HUMANS: “soft”

  small forces, large distances

- MATERIALS: “hard” (Piezoelectrics; springs, etc.)

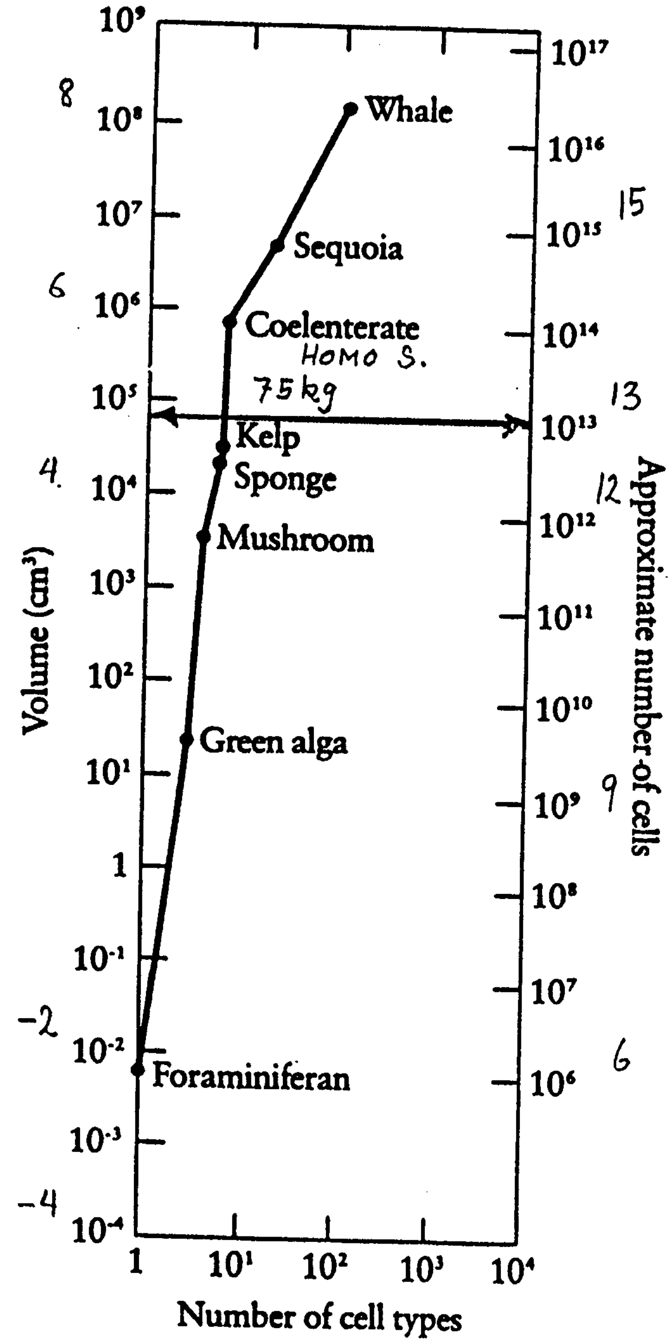
  large forces, small distances

MAN AS SEEN BY • • •

Physicist	10^{23} atoms; Å scale
Chemist	electronic bonds (eV)
Biologist	10^{11} - 10^{12} cells; μm scale
•	
•	
•	
EE	neural net
Physiologist	walking creature; meter scale
	running creature
	lifting creature
	• • •
Cosmologist	10^{-23} κοσμος; parsec scale
Poet	The Seven Ages of Man
Psalmist	What is Man, that Thou art mindful of him? 8:4

MAN-SIZED UNITS

MASS	$m_m =$	1 - 10 kg (10 - 100 N force)
LENGTH	$\ell_m =$	0.001 - 1 m
TIME	$t_m =$	0.1 - 10 s
ENERGY	$E_m =$	0.01 - 100 J
VELOCITY	$v_m =$	0.01 - 10 m/s
POWER	$P_m =$	0.001 - 1000 W



Human ($\rho \sim 1$)

$7.5 * 10^4$ cm^3

$\sim 10^{13}$ cells

CELLS

DC POWER	0
BIT	1
DATA	10^3
INFORMATION	10^6
KNOWLEDGE	10^9
UNDERSTANDING (?)	10^{12}
WISDOM (?)	10^{15}

SUMMARY

- Generators/Storage - Hardware
  Now: "single transistor" stage; poor impedance, elastance matches
  Future: "IC; VLSI;" impedance, elastance matches
- "Piezo-power-pixels" embedded in micro-scale grid with intelligent accumulation/management
- Unobtrusive, casual generation, with 5 to 10 W output
  "Fatigues without fatigue"
- Intelligent super-low-level electronics and power conserving software
- Software
  Now: "ASIC" hardware, application specific
  Future: "ASIC" software; software specifically crafted to the task

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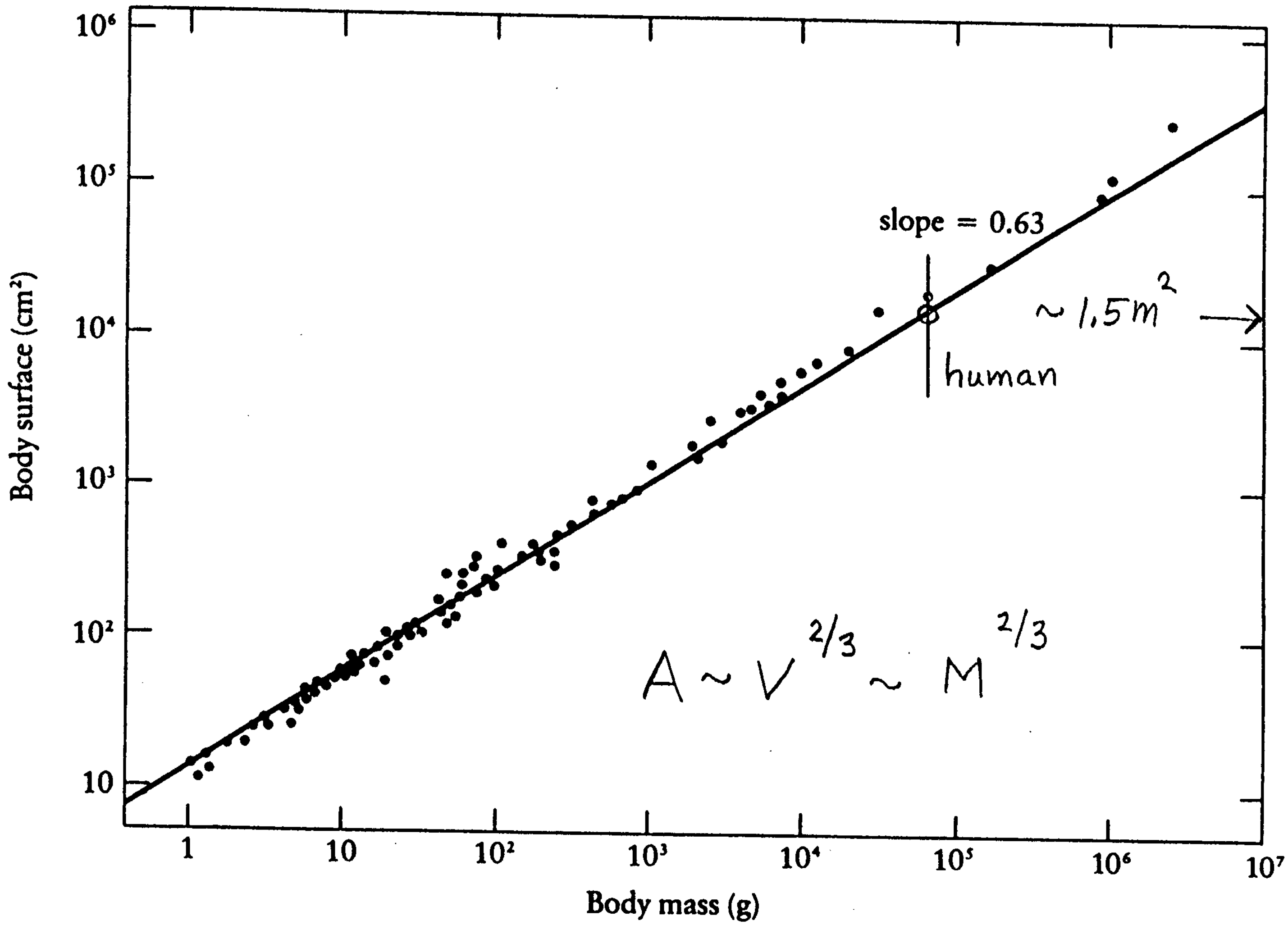
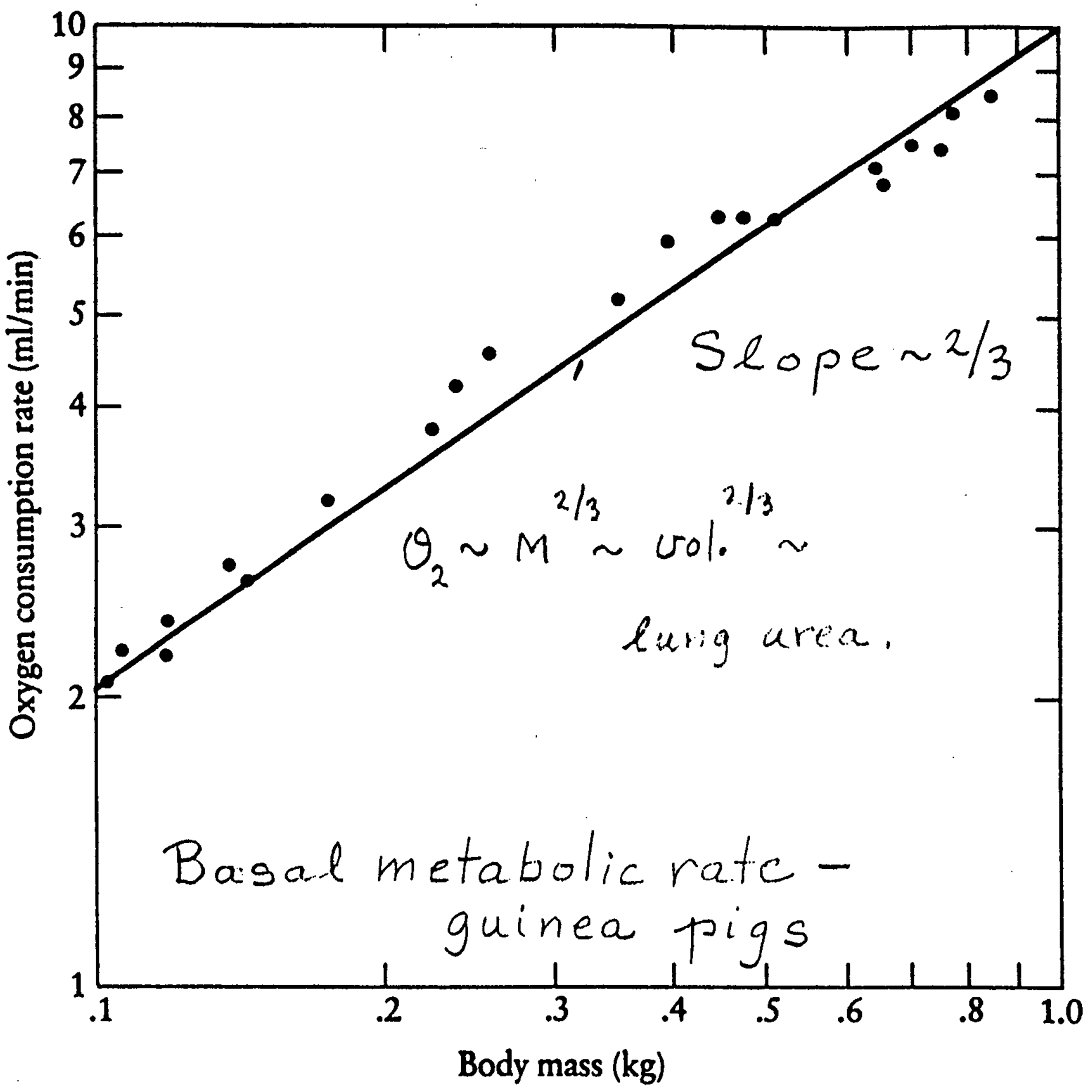
The dimensional formulas for several physical variables.

	MLT (or MLTΘ)	FLT (or FLTΘ)
Length, *l*	[L]	[L]
Time, *t*	[T]	[T]
Force, *F*	$[MLT^{-2}]$	[F]
Area, *A*	$[L^2]$	$[L^2]$
Frequency, *f*	$[T^{-1}]$	$[T^{-1}]$
Mass, *m*	[M]	$[FL^{-1}T^2]$
Velocity, *v*	$[LT^{-1}]$	$[LT^{-1}]$
Acceleration, *g*	$[LT^{-2}]$	$[LT^{-2}]$
Pressure, *P*; stress, *s*	$[ML^{-1}T^{-2}]$	$[FL^{-2}]$
Energy (work), $\mathcal{E}$	$[ML^2T^{-2}]$	[FL]
Dynamic viscosity, μ	$[ML^{-1}T^{-1}]$	$[FL^{-2}T]$
Surface tension, $\mathcal{S}$	$[MT^{-2}]$	$[FL^{-1}]$
Mass density, ρ	$[ML^{-3}]$	$[FL^{-4}T^2]$
Modulus of elasticity, *E*	$[ML^{-1}T^{-2}]$	$[FL^{-2}]$
Specific heat at constant pressure, C_p	$[L^2T^{-2}\Theta^{-1}]$	$[L^2T^{-2}\Theta^{-1}]$
Thermal conductivity, *k*	$[MLT^{-3}\Theta^{-1}]$	$[FT^{-1}\Theta^{-1}]$



Body surface (cm²)
10⁶
10⁵
10⁴
10³
10²
10
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
Body mass (g)
slope = 0.63
human
~ 1.5 m²
A ~ V^{2/3} ~ M^{2/3}



10
9
8
7
6
5
4
3
2
1
Oxygen consumption rate (ml/min)
.1
.2
.3
.4
.5
.6
.8
1.0
Body mass (kg)
Slope ~ 2/3
$O_2 \sim M^{2/3} \sim vol.^{2/3} \sim$
lung area.
Basal metabolic rate –
guinea pigs

"HISTORY AND STATUS OF PERSONAL POWER DEVICES FOR THE COMMERCIAL MARKET"

Mr. John Hutchinson

Baygen
Constanta, South Africa 7800

SYNOPSIS : SPRING POWERED DEVICES

The BayGen® Group was established in 1994 to develop and exploit the concept of Personal Power Generation (PPG) and its current products include radios and a flashlight. A PPG system enables human mechanical energy to be stored indefinitely and without decay. It delivers this energy in electrical form, upon demand, and in controllable fashion. PPG units may be integral with the power consuming device, as in the Freeplay® radio and flashlight, or they may be as separate packs designed for emergency or every day power sources for devices like telephones, navigating aids and radio/cassette players. So far BayGen® has confined its efforts to PPG systems where the human input is intentional and not incidental.

Present Baygen® products use strip steel springs as the primary storage device. These springs are configured in a constant force (negator) arrangement. The steel spring is energised by winding it from one spool to another against the pre-form. As the spring returns to its original position it applies a rotational torque to a transmission, whose output drives a direct current generator. This produces between 0.1w and 1.5w of power. Constant force springs offer excellent ergonomic power absorption qualities, they may be wound up slowly or very fast. Because electrical power is generated relatively slowly electromechanical losses are minimized. All-gear transmissions can be noisy in certain applications (e.g. radio), and to alleviate this a flexible drive may be used in the last stage.

Only the amount of work actually exerted by the user, less an allowance for inefficiencies, may be redelivered. PPG systems are therefore more limited by human capacity than by technology. Input mechanisms should provide for the most comfortable and ergonomically efficient acceptance of human mechanical energy. By extending the human fatigue point, larger amounts of energy may be delivered to and stored by the system. A 60-turn spring stores approximately 500 joules of mechanical energy. Current systems have an overall efficiency of approximately 40% and about 200 joules electrical are delivered.

Although negator springs have constant force characteristics they do not provide constant torque. Torque decays to about 75% of initial value during the unwind cycle. In order to produce constant power a regulation device is necessary. BayGen® has developed and uses various designs. These include interim or buffer storage devices using a capacitor or a rechargeable battery. With suitable power regulation, spring based systems are able to power a wide range of electronic products.

BayGen

BAYGEN®
FREEPLAY® RADIO II

Introduction

The Freeplay® Radio utilises personally generated power, and has no need for batteries or an external power source. The energy storage and release mechanism is based upon energising a textured carbon steel spring by winding it from one spool to another. As the spring returns to its original position, it releases it's energy and applies a rotational torque into a transmission. The transmission consists of a three stage gearbox, which speeds up the input rotation by a factor of 1:1000. The transmission output drives a direct current generator which produces up to 100mW of power. This is used as the energy for a radio receiver. The structural components for the Freeplay® Radio consist of injection mouldings made from a number of different materials. Other components include the carbon steel spring, electronics, PC board, switches, fasteners, etc. The injection moulded components require original tooling.

Specifications

Power Source: Internal	B-Motor textured carbon steel spring, 10m x 50mm x 0,2mm, driving a DC generator through a transmission. 60 Winds provides full energy storage.
Power Source: External	Optional DC adaptor (centre positive) 3V-12VDC/200mA.
Spring Saver:	This circuit allows playtimes of up to 60 minutes at low volumes. At low power demand, this device stores generated energy not required by the radio in a capacitor. A control circuit regulates the motor/capacitor duty cycle and results in a lower unwind rate.
Frequency Range:	FM 88 – 108MHz AM 500 – 1700KHz
Generator:	Mabuchi RF-500TB D.C. motor "in reverse", producing 35mA, 3V at 1500 r.p.m.
Speaker:	Size 4 inch Impedance 8 ohms Output 5W (Max)
Antenna System:	FM Telescopic Antenna AM Built-in Ferrite Bar Antenna
Dimensions:	Height 200mm Width 200mm Length 290mm Weight 2,4kg

The **Freeplay®** flashlight is designed to be the last flashlight a user ever needs to buy. It operates independent of any commercial electricity source yet it has the ability to use such sources if available.

The **Freeplay®** flashlight works by using human energy stored in a spring or by a rechargeable battery.

SPRING POWER OPERATION

- A winding handle energizes a constant force spring. Sixty turns of the handle, taking 20–30 seconds, fully energizes this spring.
- Spring energy may be used to power the bulb directly, or to charge the battery. When used to charge the battery consecutive spring discharge cycles may be dumped into the battery to increase its charge level.
- One spring discharge provides four minutes of shine time. Multiple spring discharges into the battery allows extended continuous shine times.
- The spring may be stored indefinitely in the wound condition. This allows instantaneous flashlight operation whenever required.
- The flashlight may be operated directly off the spring even when the battery is flat.
- The spring lifetime is 10,000 full wind/discharge cycles, after which its storage capacity degrades gradually.
- The spring is equipped with a mechanical brake. If the flashlight is switched off before the spring is fully discharged any wind still on the spring is preserved.

BATTERY OPERATION

- The flashlight is equipped with a rechargeable battery.
- The battery is charged either by one or more spring discharges, or by a mains adapter. Each spring discharge provides four minutes of shine time and a full mains charge gives two hours of shine time.
- This high specification battery has a lifetime of 5 - 10 years, which may be exceeded if operating instructions are followed. Should it be necessary to replace the battery the user easily does this.
- The battery is recyclable and carries the RBRC battery recycling licence and seal.

FEATURES

- 60 Turn spring.
- Hi impact ABS casing and rugged constitution.
- Water resistant sealing.
- Flasher function.
- High efficiency 2,3V 350mA bulb.
- Spare bulb.
- Patented HI GAIN® lens.
- D.C. input socket.
- Mains adaptor (supplied)
- Car adaptor (optional).
- Solar charger (optional).
- Weight 1,8 kg.
- Dimensions 240 x 160 x 120 mm.

DESIGN CONFIGURATION

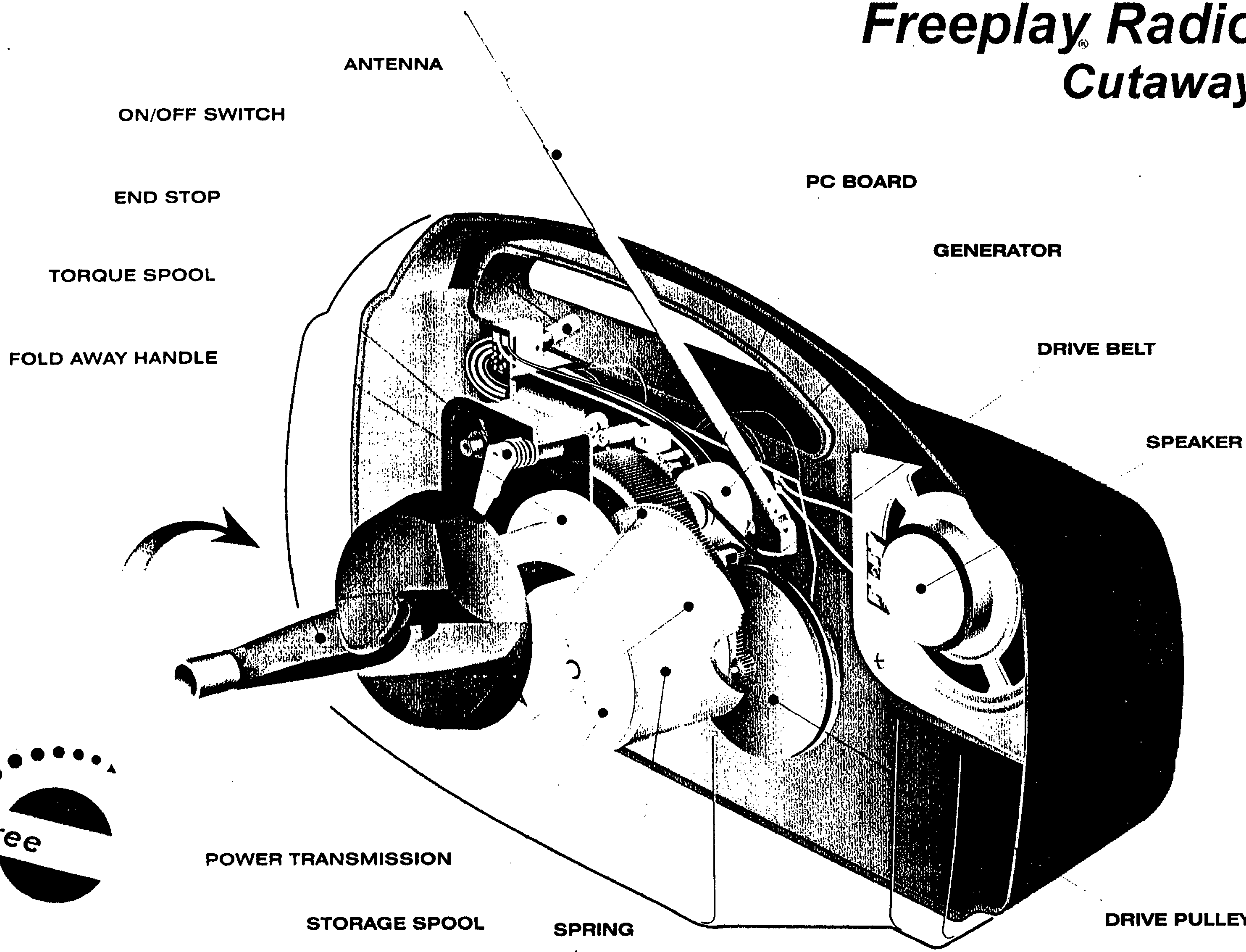
STANDARD VERSION

- First production models feature the flashlight as a single unit.
- The rechargeable battery, PCB and switches are housed in the body of the flashlight, and operation is as per a regular lantern.

UPGRADED VERSION

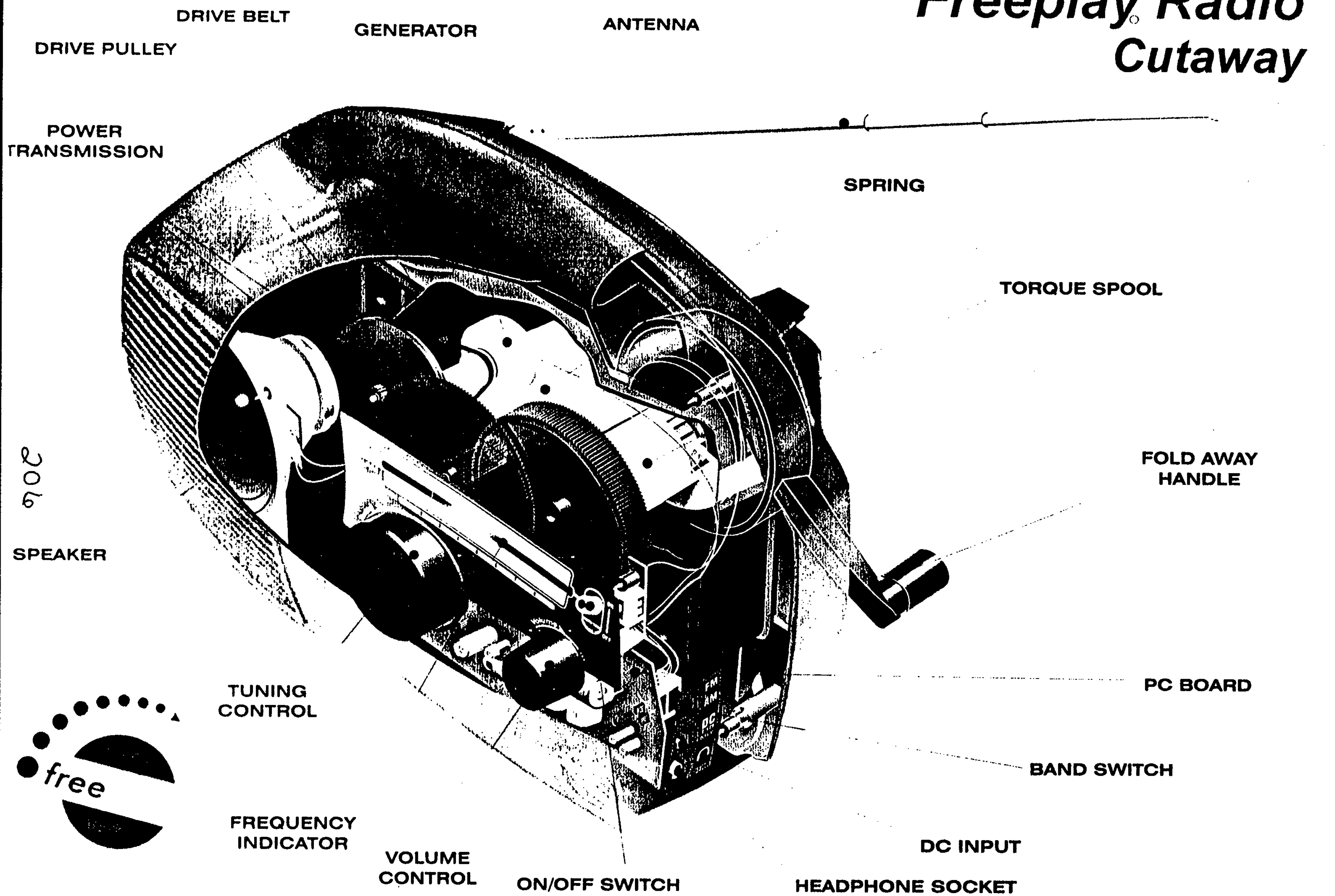
- An upgraded version which features a detachable lens assembly is scheduled for later production.
- The rechargeable battery, PCB and switches are housed in a detachable front unit which may be removed from the main body containing the spring engine.
- This unit operates independently as a mini flashlight under battery power.
- The battery compartment pivots to provide a handle.
- To charge the batteries from mains power or by spring discharge the detachable unit is remounted onto the main body.
- When attached, the flashlight operates similarly to the standard version from either spring or battery power.

Freeplay® Radio Cutaway



free

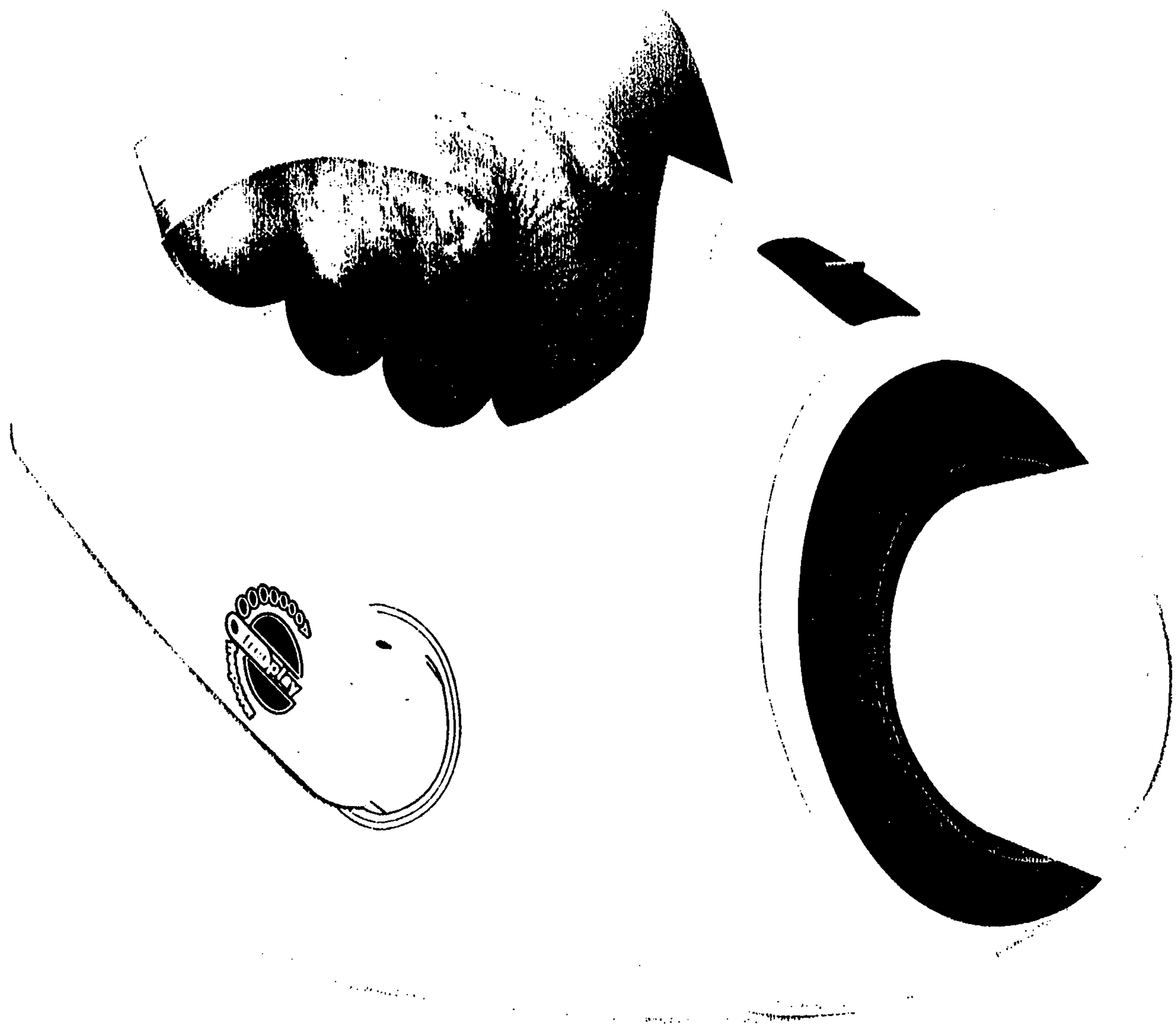
Freeplay Radio Cutaway



free

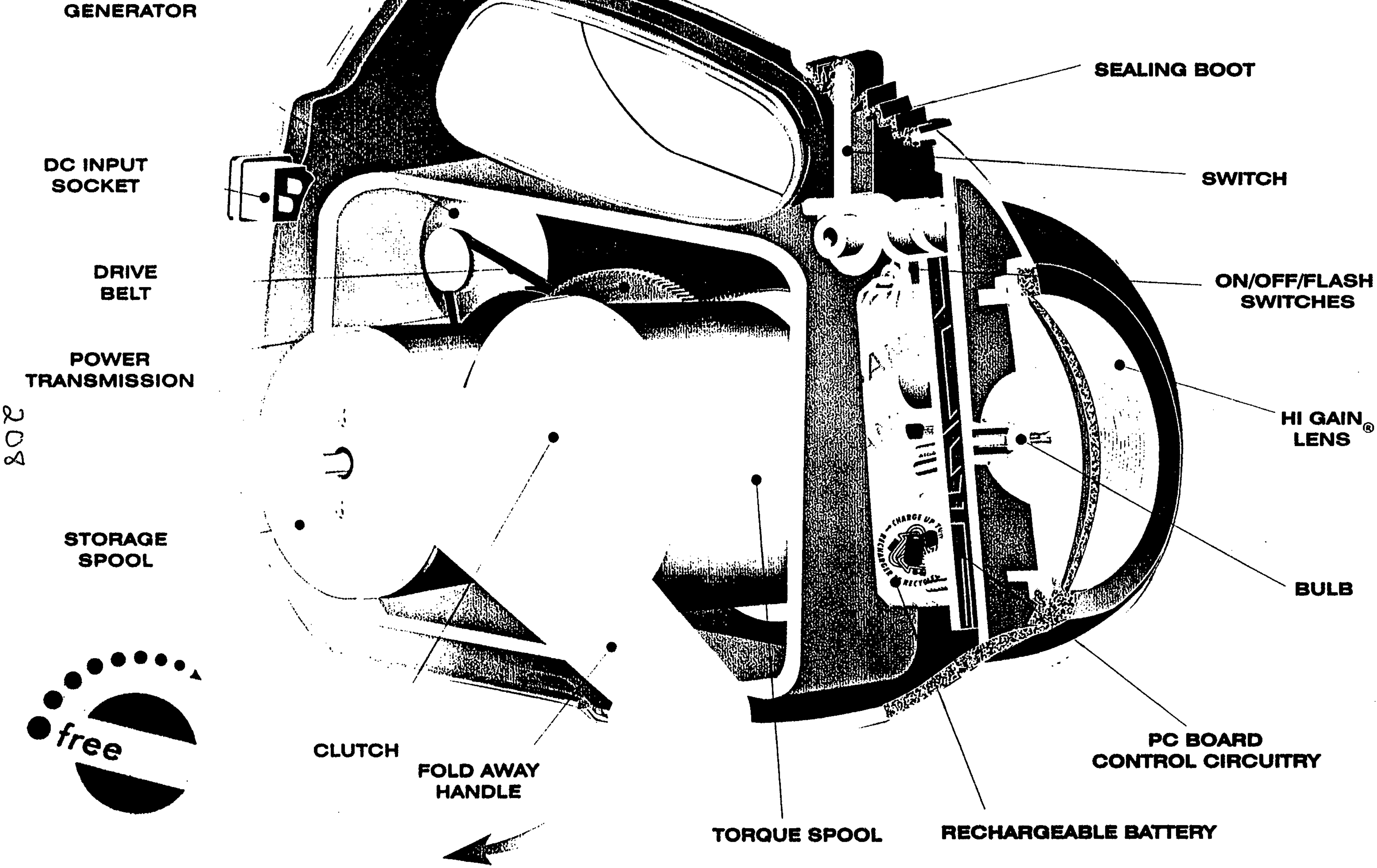
206

Freeplay® Flashlight



207

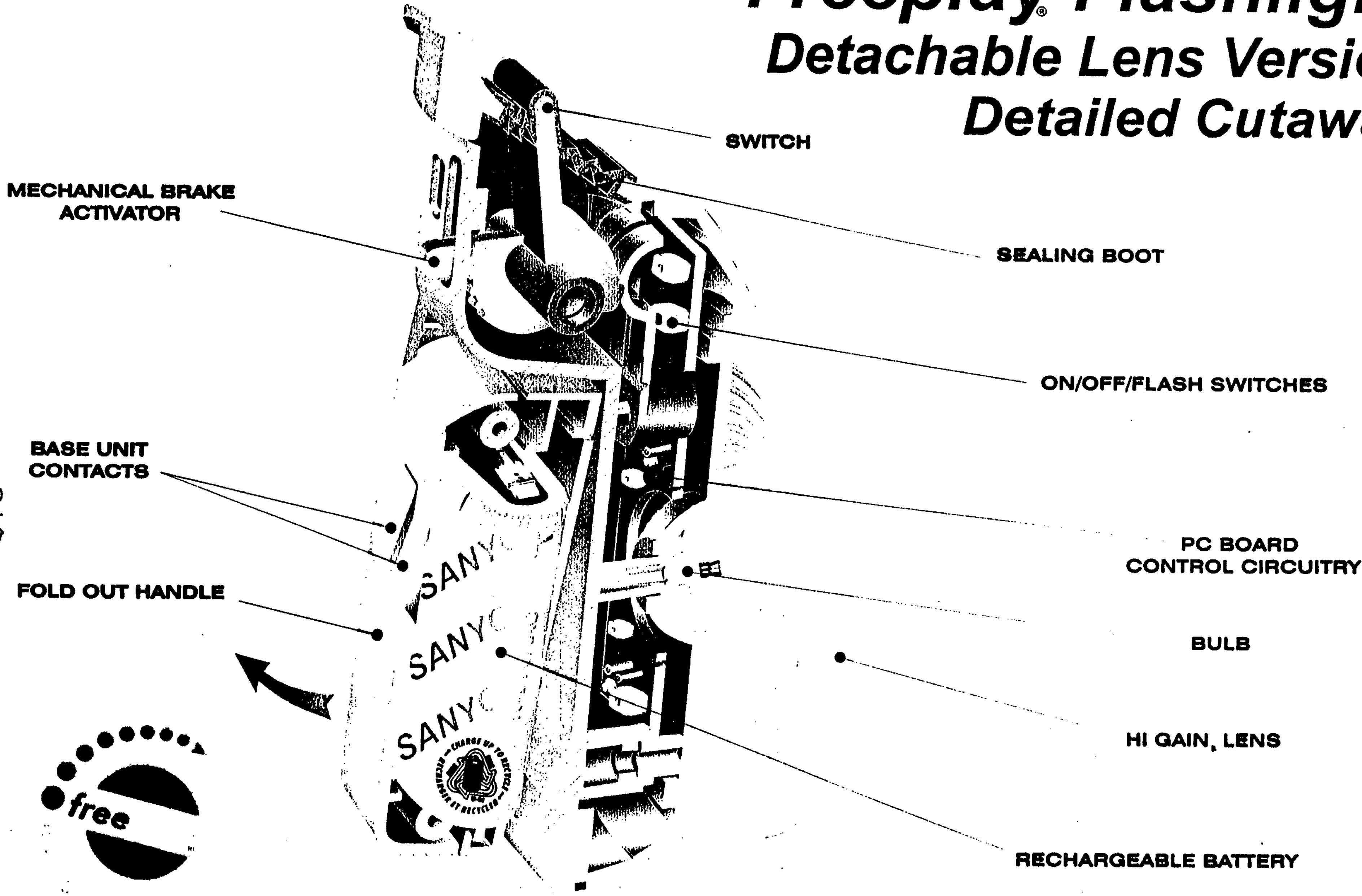
Freeplay® Flashlight Cutaway



Freeplay Flashlight
Detachable Lens Version

209

Freeplay® Flashlight
Detachable Lens Version
Detailed Cutaway



"PHYSIOLOGICAL FACTORS THAT MAY LIMIT AND TECHNIQUES THAT MAY ENHANCE HUMAN PERFORMANCE"

Dr. Ellen L. Glickman-Weiss

Kent State University
Kent, OH 44242

PHYSIOLOGICAL FACTORS THAT MAY LIMIT AND TECHNIQUES THAT MAY ENHANCE HUMAN PERFORMANCE

E. Glickman-Weiss PhD, FACSM

Exercise Sciences Laboratory

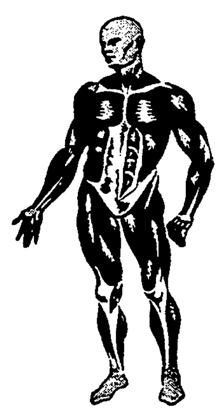
Kent State University

Kent, Ohio

VO_2max (maximum oxygen consumption)

"The region where oxygen uptake plateaus and shows no further increase, or increases slightly, with an additional workload"

"Maximum capacity to take in room air and distribute it to the working skeletal muscles"



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Training State, Disease State
Frequency, Intensity, Duration, Mode

Clothing → **Acclimation** **Acclimatization**

Cardiovascular

Central
$Q = HR \times SV$

Peripheral
$a\text{-}vO_2\ diff = CaO_2 - CvO_2$

Altitude
Heat
Cold
$+G_Z$

Gender
Age
Genetic (Individual Differences)
Body Size (morphology, % Fat)

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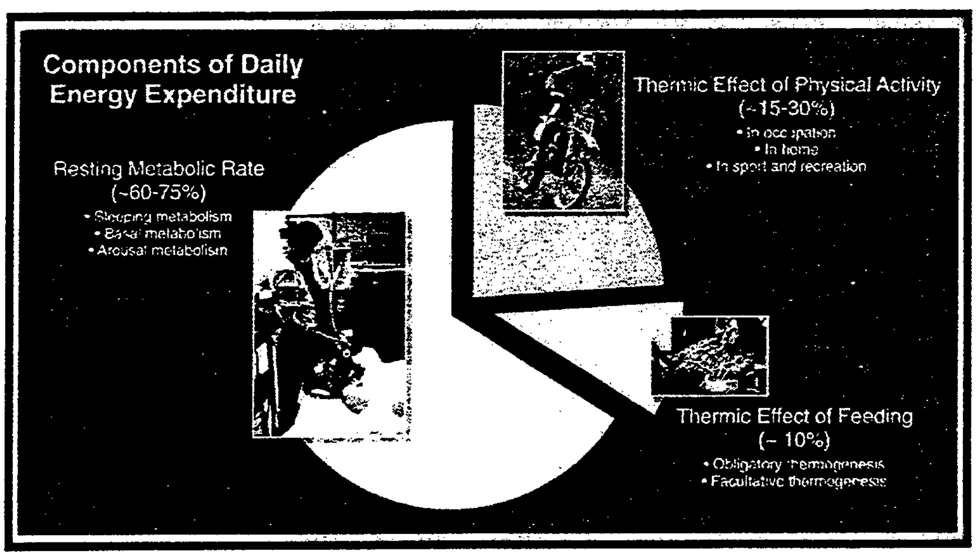
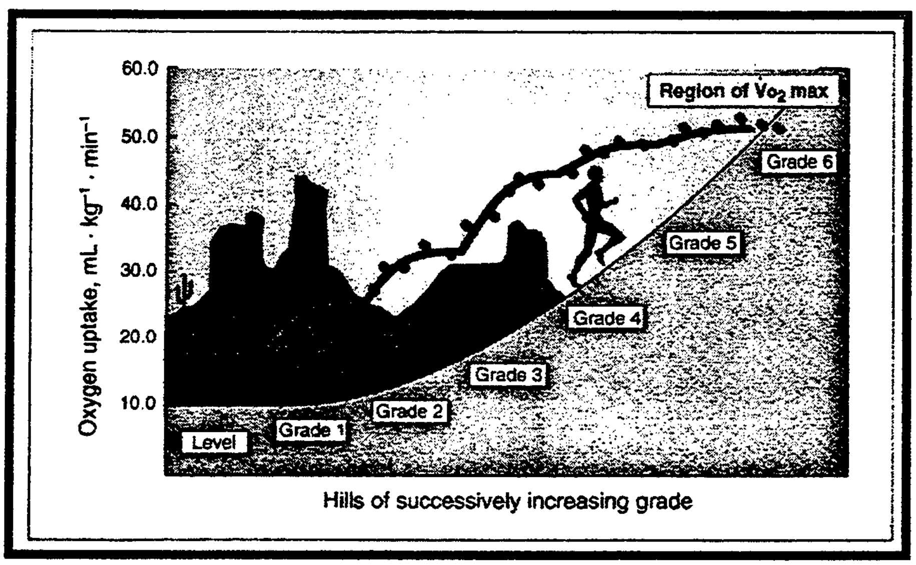
Components of Daily Energy Expenditure

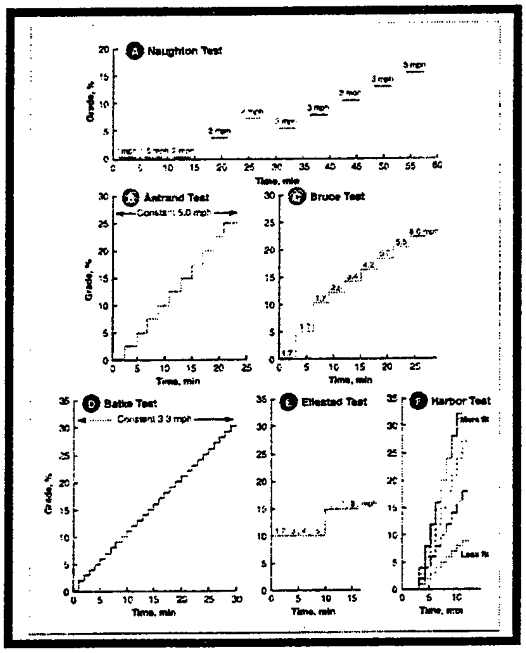


Determining Energy Expenditure of Specific Activities

Portable Spirometry

VO_2 with Increasing Intensity (% Grade)

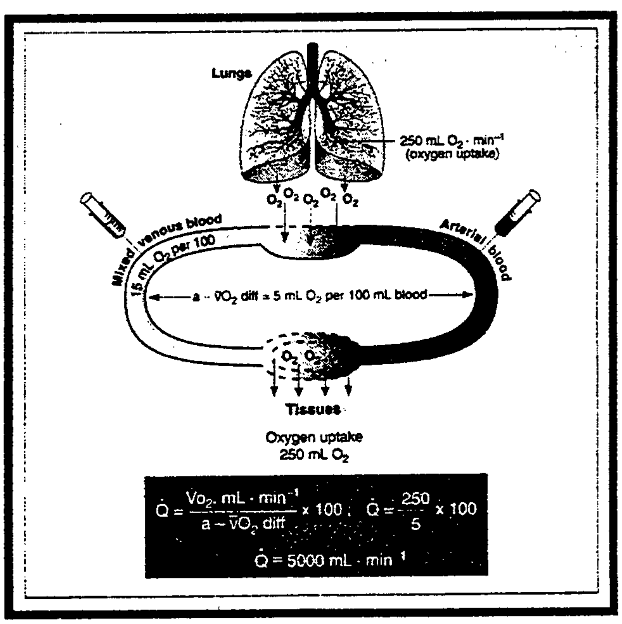




Treadmill Protocols to Measure VO_2max

- Naughton Test
- Astrand Test
- Bruce Test
- Balke Test
- Ellestad Test
- Harbor Test

Kent



Fick Principle

Measurement of cardiac output

$VO_2 = Q * a\text{-}vO_2$ diff

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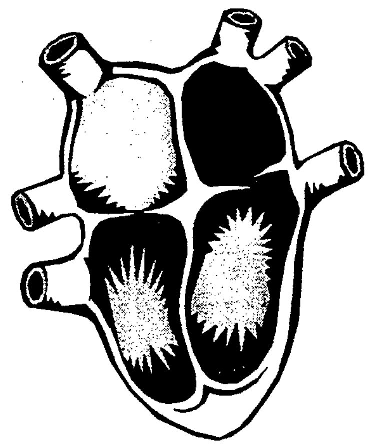
Cardiovascular Variables

- Cardiac Output ($mL \cdot min^{-1}$)
  - The amount of blood pumped by the heart per minute
- Stroke Volume (mL)
  - Quantity of blood ejected from the heart with each stroke
- Heart Rate ($beats \cdot min^{-1}$)
  - Rate of pumping



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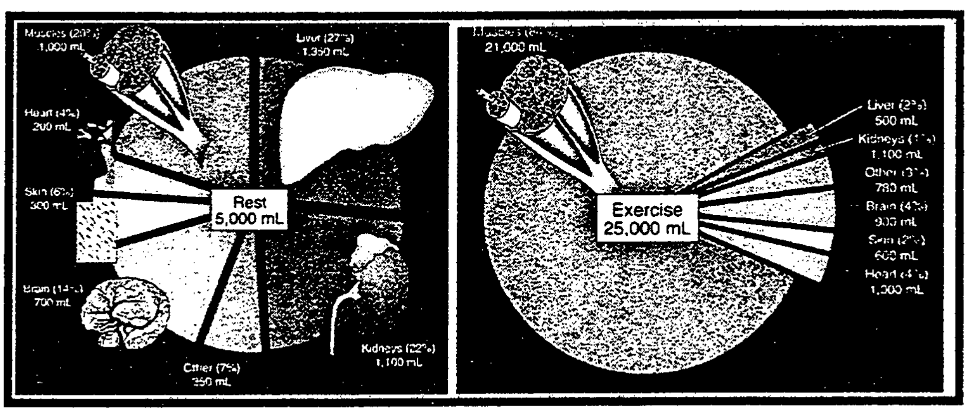
Cardiac Output Distribution



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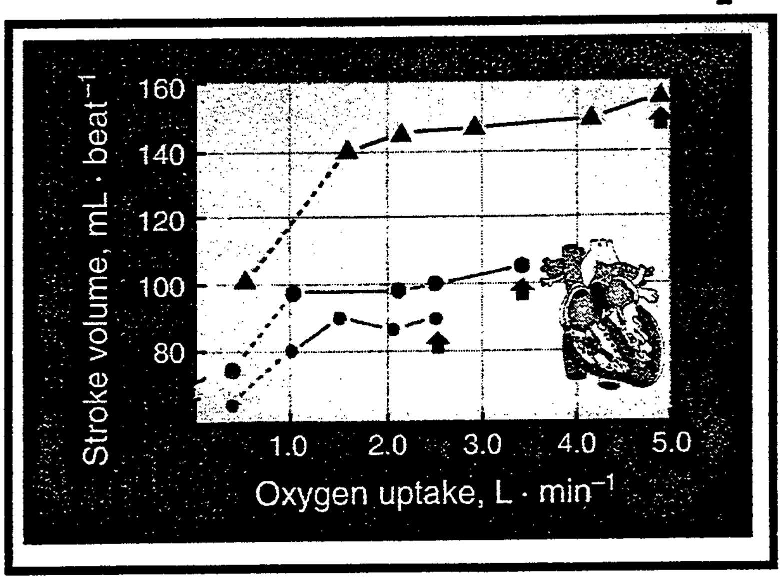
Cardiovascular Variables and Training

	Cardiac Output =	HR x	SV
Rest			
Untrained	5000 mL•min^{-1}	70 beats•min^{-1}	71 mL
Trained	5000 mL•min^{-1}	50 beats•min^{-1}	100 mL
Maximal Exercise			
Untrained	22000 mL•min^{-1}	195 beats•min^{-1}	113 mL
Trained	35000 mL•min^{-1}	195 beats•min^{-1}	179 mL

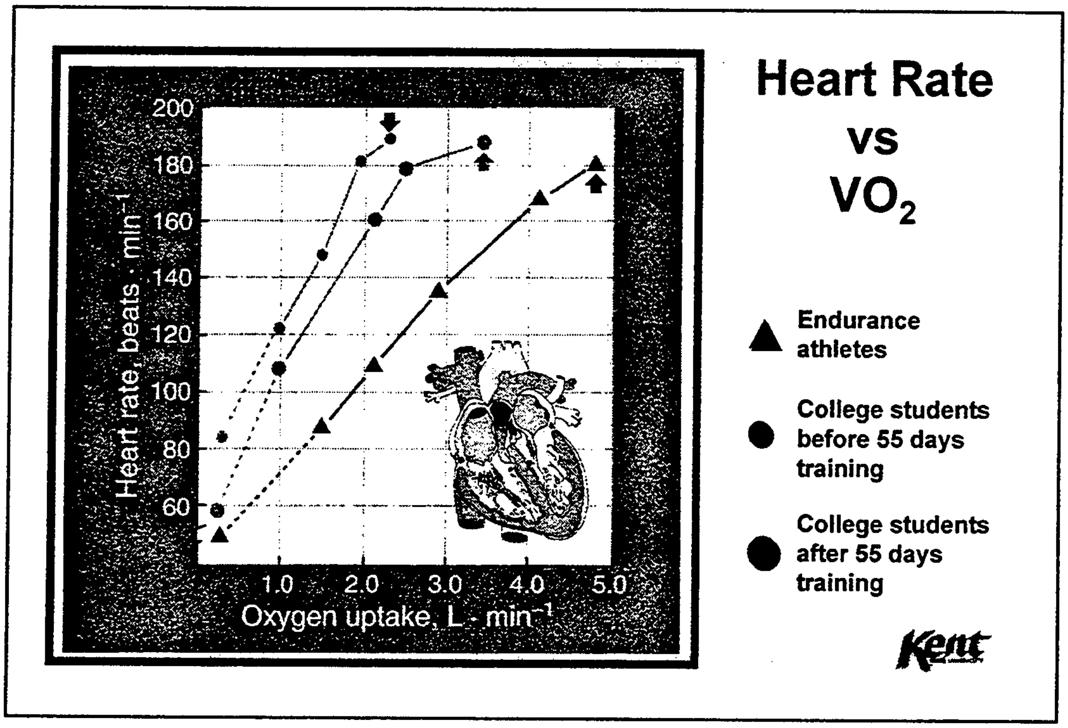
Stroke Volume vs VO_2

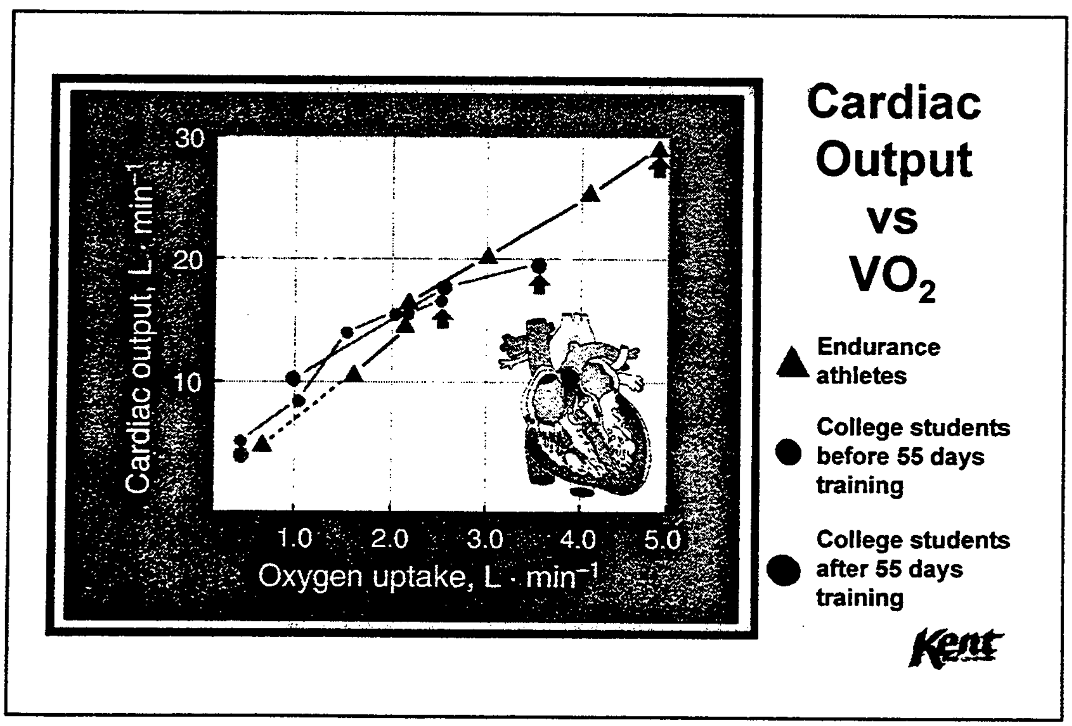


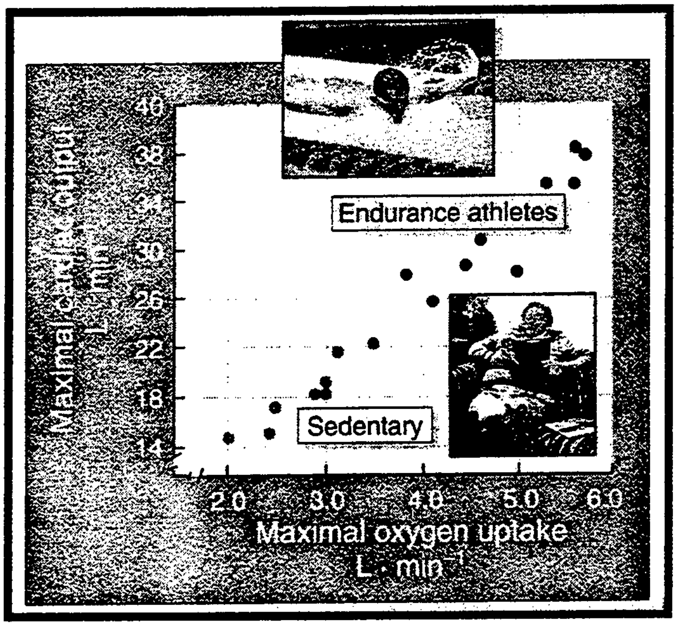
Endurance athletes

College students before 55 days training

College students after 55 days training


Heart Rate vs VO_2
200
180
160
140
120
100
80
60
Heart rate, beats · min-1
1.0
2.0
3.0
4.0
5.0
Oxygen uptake, L · min-1
Endurance athletes
College students before 55 days training
College students after 55 days training
Kent

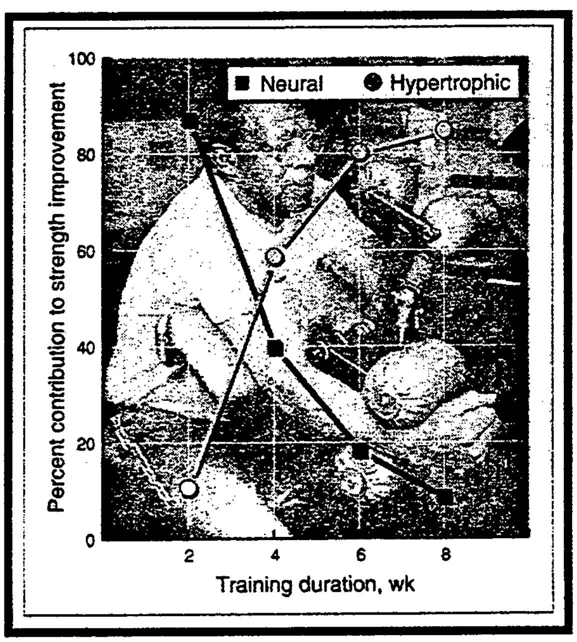

Cardiac Output vs VO_2
30
20
10
Cardiac output, L · min-1
1.0
2.0
3.0
4.0
5.0
Oxygen uptake, L · min-1
Endurance athletes
College students before 55 days training
College students after 55 days training
Kent



Cardiac Output vs VO_2max

Trained vs Untrained

Kent



Improvements in Strength

- Neural contribution
- Hypertrophic contribution

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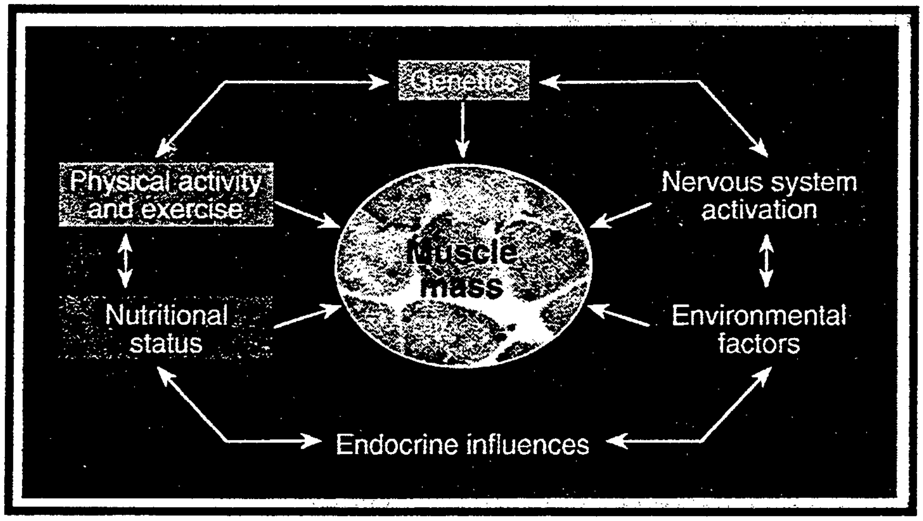
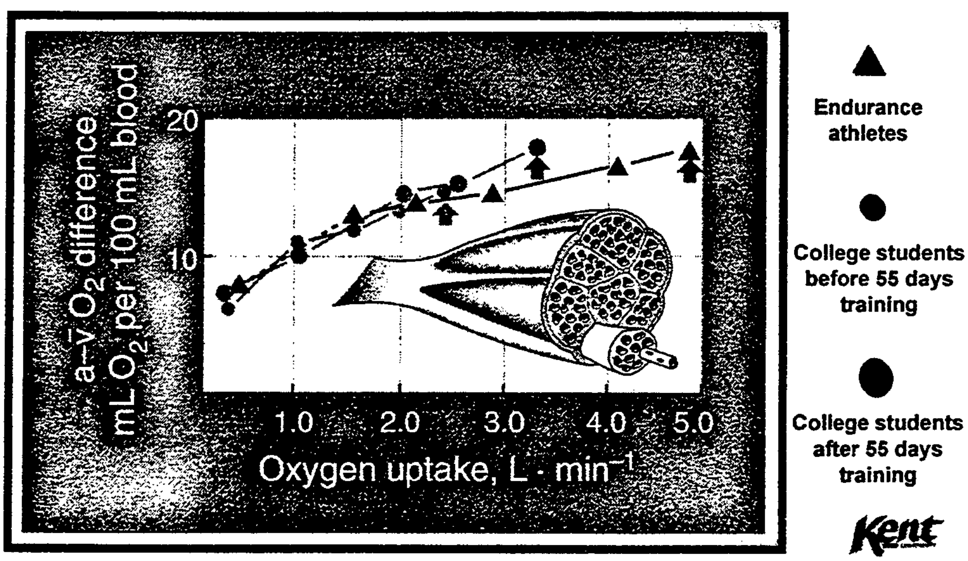
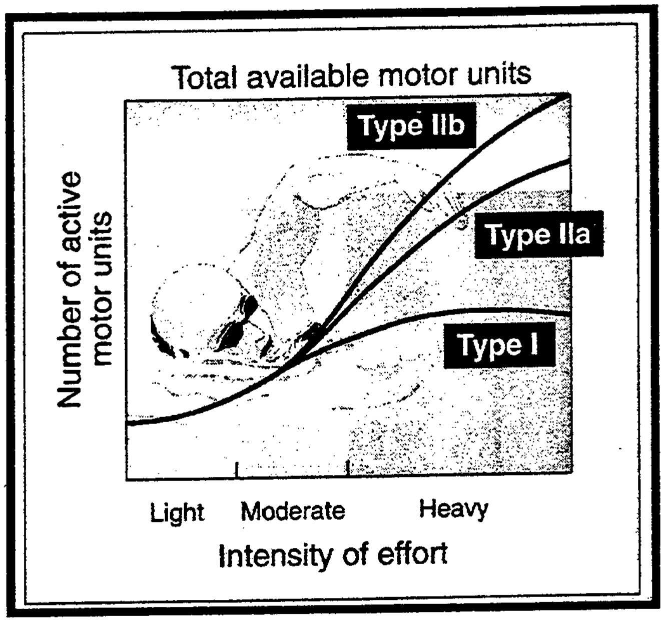
Factors Determining Muscle Mass



a-vO_2 difference vs VO_2



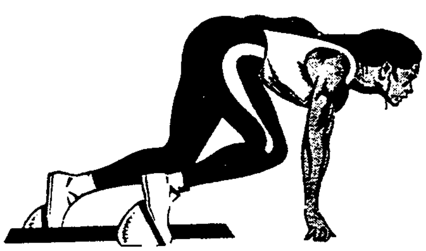


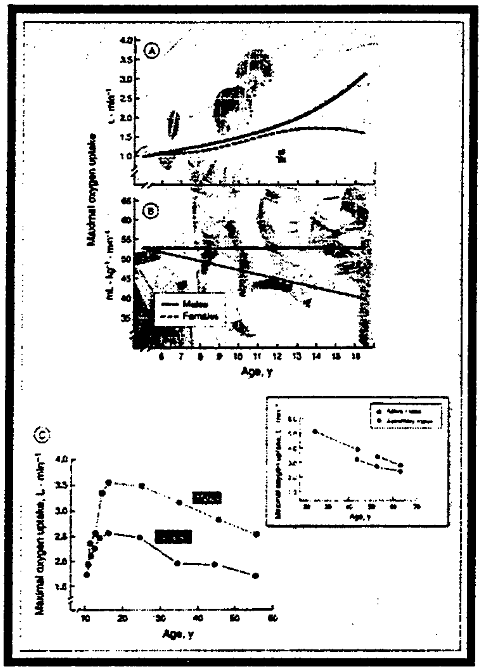
Muscle Fiber and Motor Unit Recruitment

Relationship to Intensity

Specificity

"A principle of training that the adaptation of a tissue is dependent on the type of training undertaken"





VO_2max in Relation to Age and Gender

A) VO_2max in children (LO_2/min)

B) VO_2max in children (ml/kg/min)

C) VO_2max males vs. females

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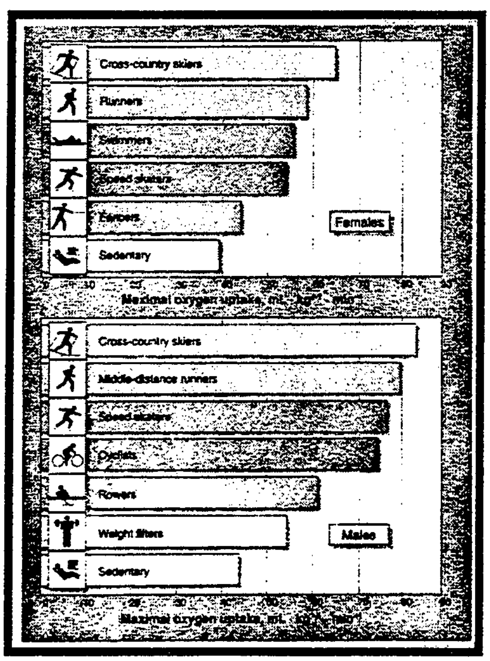
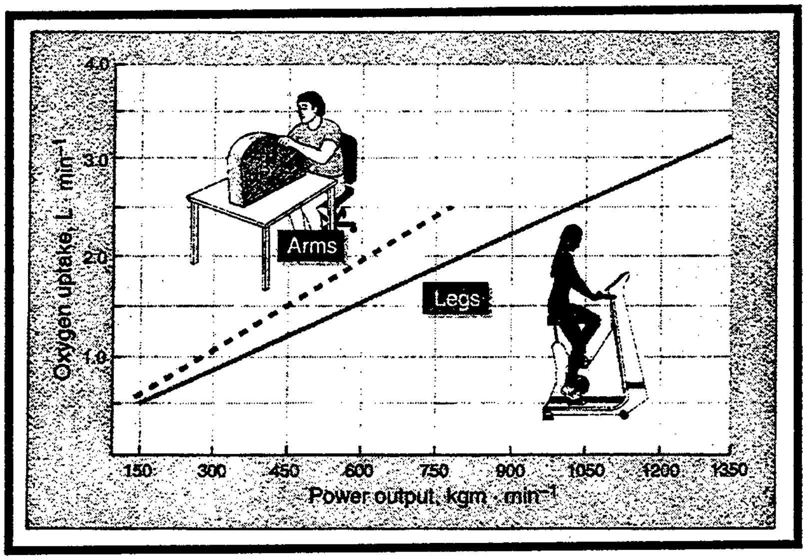


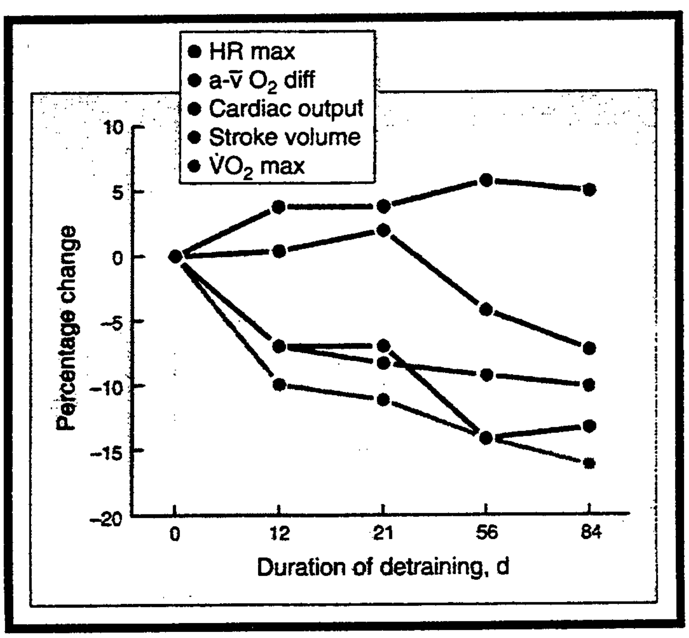
VO_2max in Olympic Caliber Athletes

- Males vs Females
- Athletes vs Sedentary Adults

Kent

VO_2: Arm vs Leg Exercise

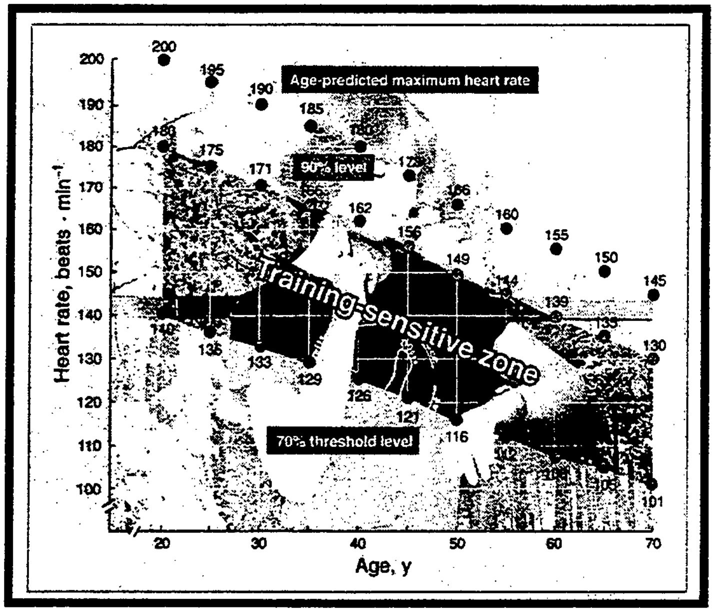




Effects of Detraining

Cardiovascular Responses

Target HR Zone for Training



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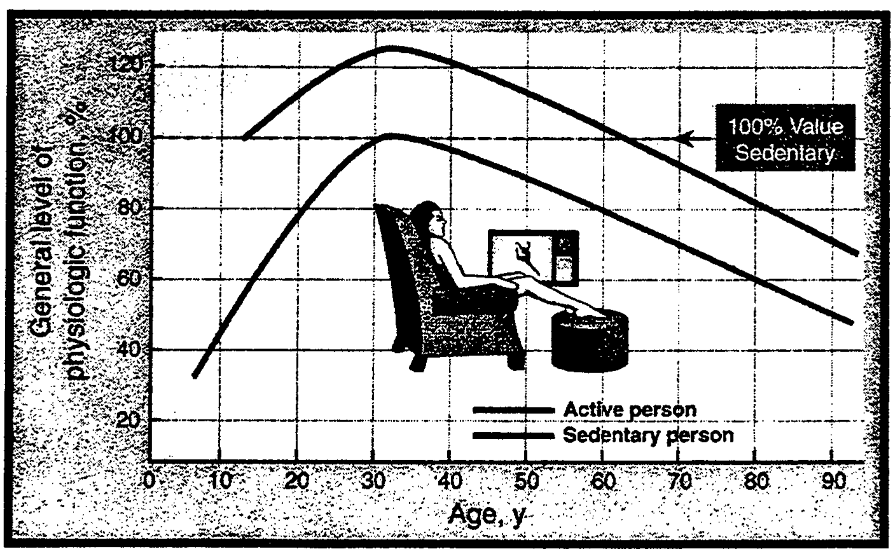
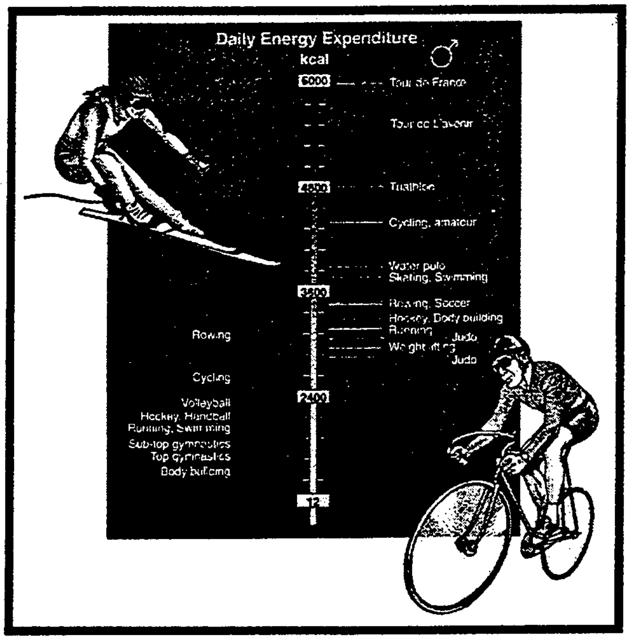
Physical Function and Aging





Daily Energy Expenditure (kcal) in Various Athletes

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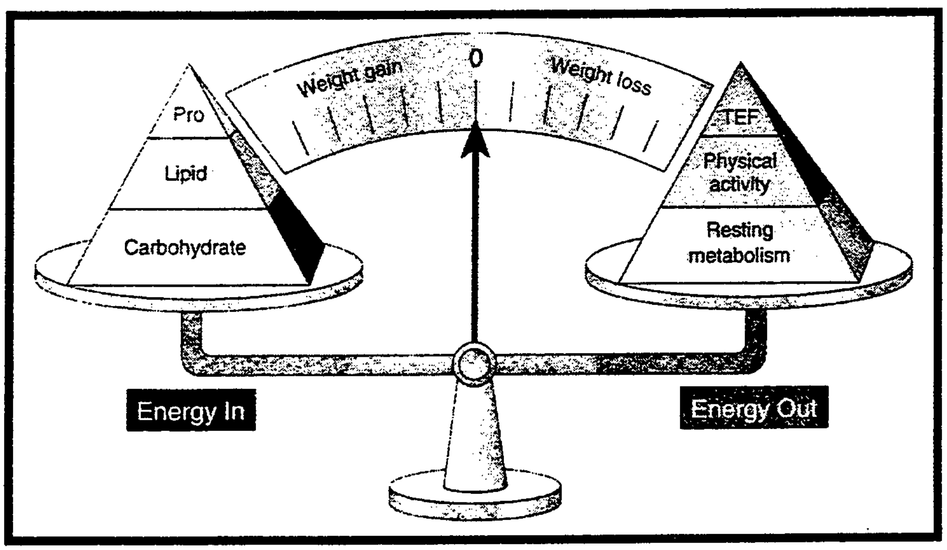
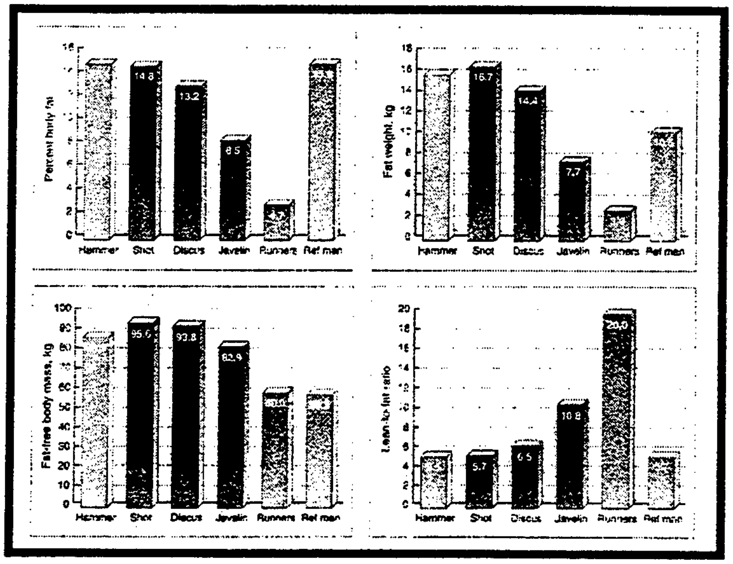
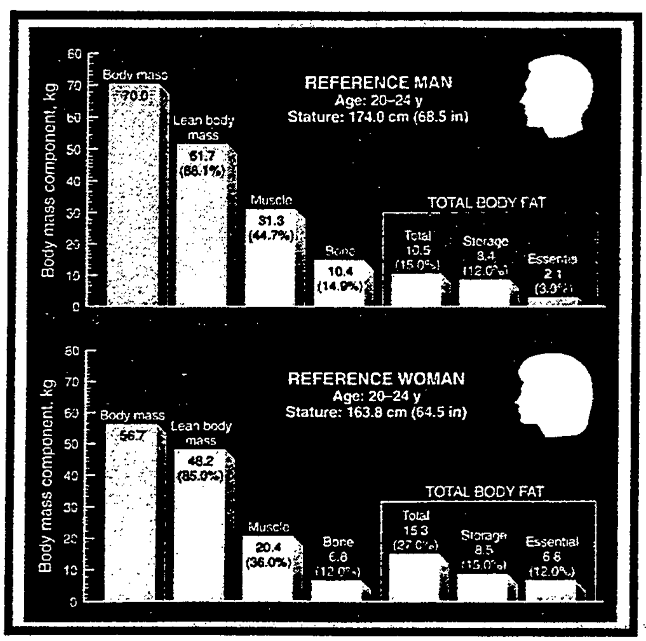
Energy Balance Equation



Body Composition of Various Athletes





Reference Man and Woman

Average % Body Fat

Study	Age Range	Stature, cm	Mass, kg	% Fat
Younger women				
North Carolina, 1962	17–25	165.0	55.5	22.9
New York, 1962	16–30	167.5	59.0	28.7
California, 1968	19–23	165.9	58.4	21.9
California, 1970	17–29	164.9	58.6	25.5
Air Force, 1972	17–22	164.1	55.8	28.7
New York, 1973	17–26	160.4	59.0	26.2
North Carolina, 1975		166.1	57.5	24.6
Army Recruits, 1986	17–25	162.0	58.6	28.4
Massachusetts, 1996	17–30	165.2	57.8	21.8
Younger men				
Minnesota, 1951	17–26	177.8	69.1	11.8
Colorado, 1956	17–25	172.4	68.3	13.5
Indiana, 1966	18–23	180.1	75.5	12.6
California, 1968	16–31	175.7	74.1	15.2
New York, 1973	17–26	176.4	71.4	15.0
Texas, 1977	18–24	179.9	74.6	13.4
Army Recruits, 1986	17–25	174.7	70.5	15.6
Massachusetts, 1996	17–30	178.1	76.4	12.9

Body Composition of Olympic Athletes

Specialty	Event	Olympics	N	Age (y)	Stature (cm)	Mass (kg)	LBM* (kg)	Body Fat (%)
Sprint	100–200 m; 4 × 100 m;	Tokyo	172	24.9	178.4	72.2	64.9	10.1
	110-m hurdles	Mexico City	79	23.9	175.1	68.4	62.8	8.2
Long-distance	3000, 5000	Tokyo	99	27.3	173.6	62.4	61.5	1.4
running	10,000 m	Mexico City	34	25.3	171.9	59.8	60.1	−0.5
Marathon	42.2 km	Tokyo	74	28.5	170.3	60.8	59.2	2.7
		Mexico City	20	26.4	168.7	56.6	58.1	2.7
Decathlon		Tokyo	26	26.3	183.2	83.5	68.5	15.0
		Mexico City	8	25.1	181.3	77.5	67.1	13.4
Jump	High, long	Tokyo	89	25.3	181.5	73.2	67.2	8.2
	triple jump	Mexico City	14	23.5	182.8	73.2	68.2	6.8
Weight	Shot, discus	Tokyo	79	27.6	187.3	101.4	71.6	29.4
throwing	hammer	Mexico City	9	27.3	186.1	102.3	70.7	30.9
Swimming	Free, breast, back,	Tokyo	450	20.4	178.7	74.1	65.1	12.1
	butterfly, medley	Mexico City	66	19.2	179.3	72.1	65.6	9.0

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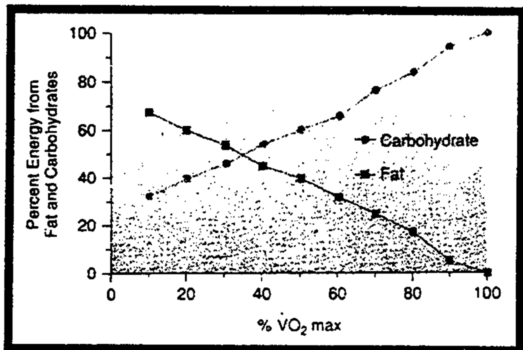
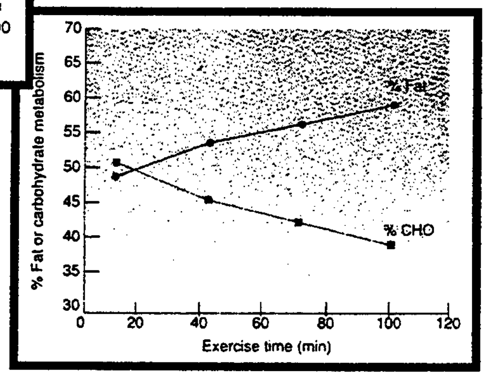


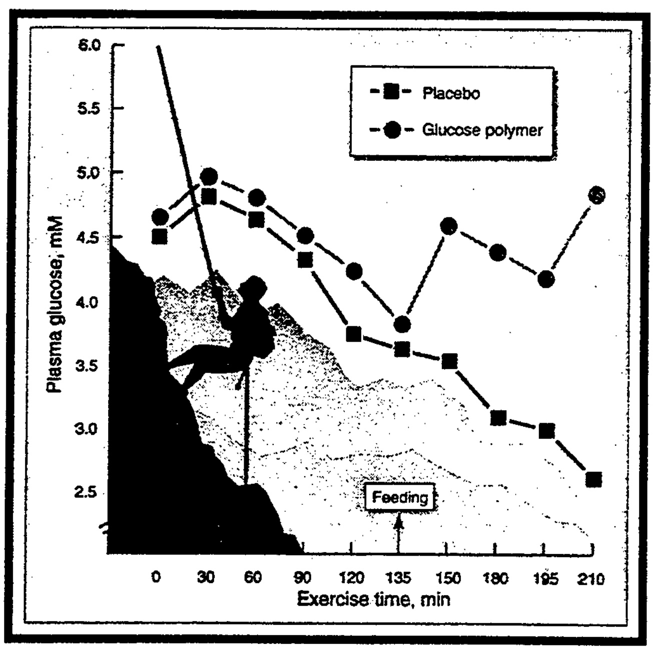
Crossover Principle

Relative to Intensity

Crossover Principle

During Prolonged Exercise





Glucose Concentration during Exercise

Placebo vs Glucose

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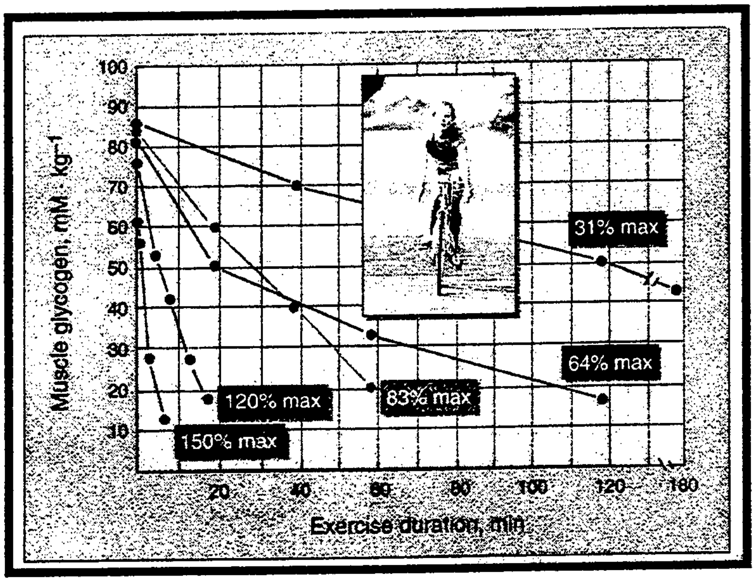
Glycogen Depletion



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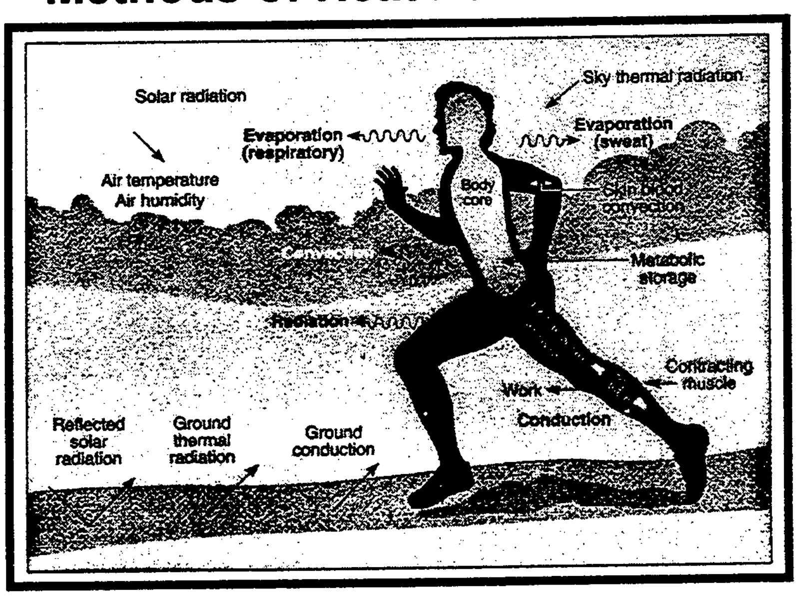
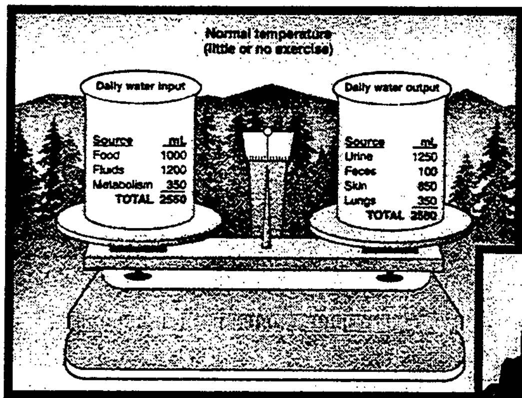
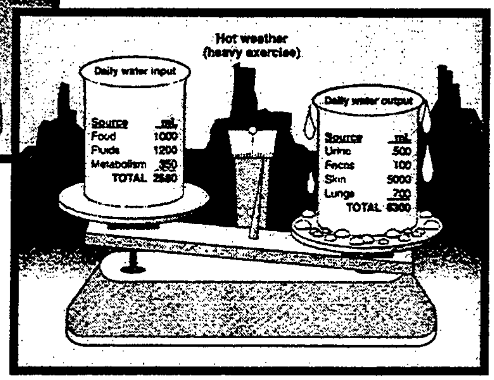
Methods of Heat Loss and Gain

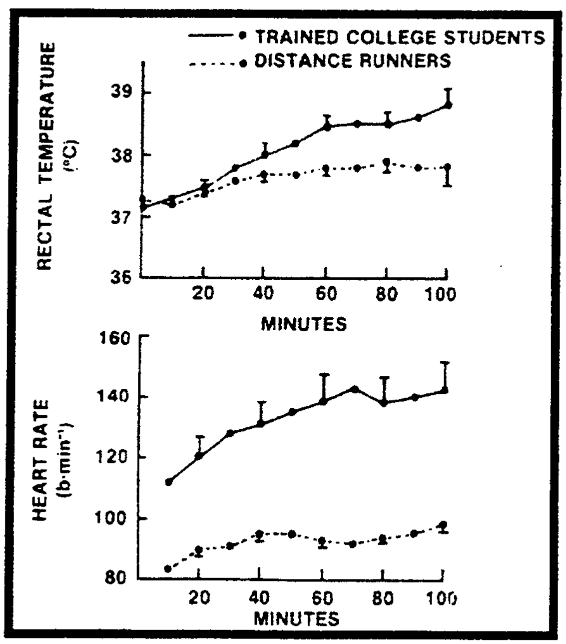




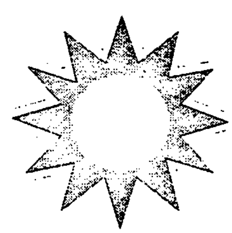
Water Balance Normal Temp
(little or no exercise)



Water Balance Hot Weather
(heavy exercise)



HR and Tre during Exercise in Dry Heat



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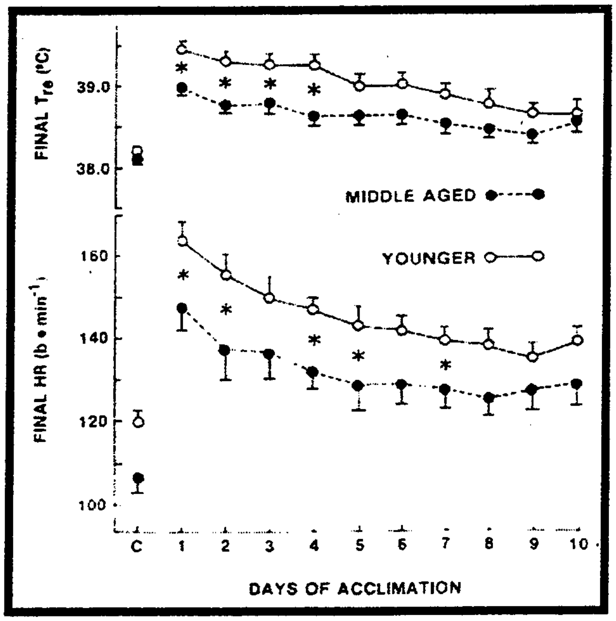
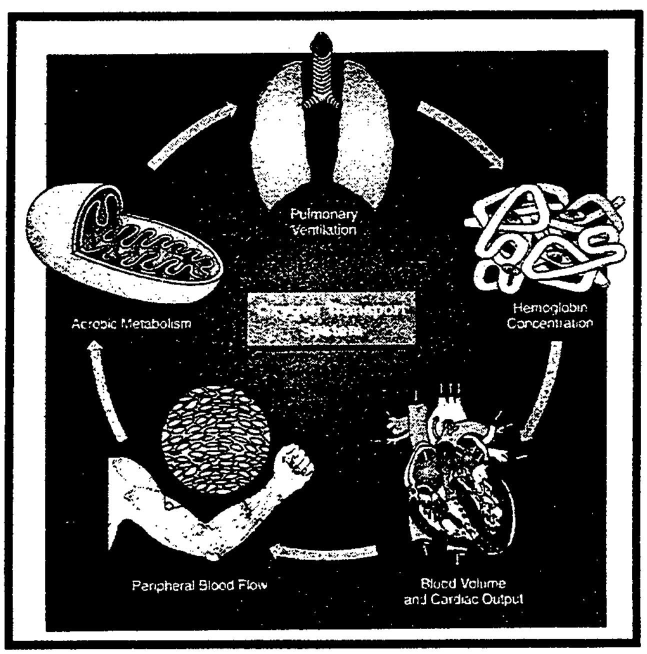


HR and Tre Effects of Acclimation

Kent



The Aerobic System

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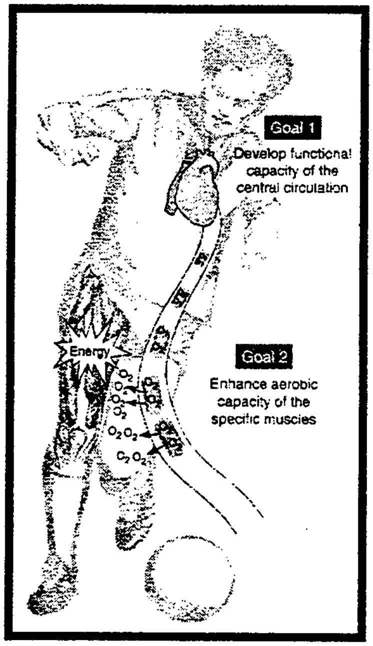

Goals of Aerobic Training

- **Delivery of Oxygen**
- **Utilization of Oxygen**

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Training State, Disease State
Frequency, Intensity, Duration, Mode

Clothing

Acclimation
Acclimatization

Cardiovascular
Central
$Q = HR \times SV$
Peripheral
$a\text{-}vO_2 \text{ diff} = CaO_2 - CvO_2$

Altitude
Heat
Cold
$+G_z$

Gender
Age
Genetic (Individual Differences)
Body Size (morphology, % Fat)

Kent

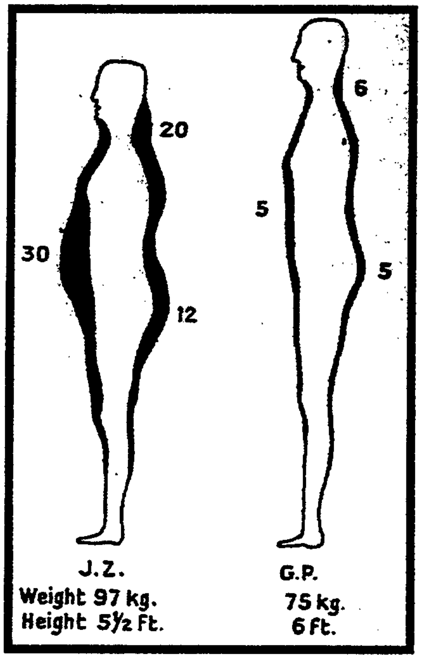
FACTORS THAT INFLUENCE PHYSIOLOGICAL AND THERMAL RESPONSES TO RESTING COLD EXPOSURE

E. Glickman-Weiss, Ph.D., FACSM

Kent State University
Exercise Science Laboratory
School of Exercise, Leisure & Sport

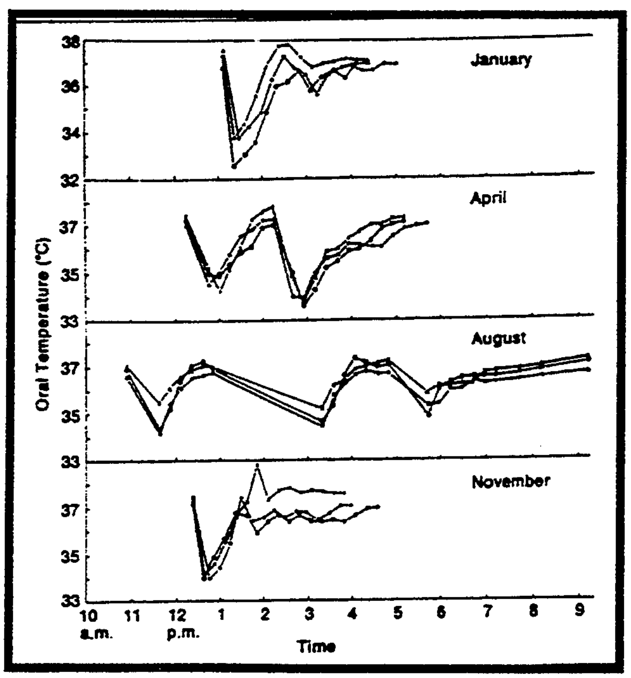
Cold Exposure Research

- Survivability: Navy dictum "You are not dead until you are warm and dead"
- Performance: Substrate utilization, delay onset of fatigue
- Insulation: Clothing vs. Body Fat



Pugh LGC and OG Edholm (1955)

Numerals indicate thickness of subcutaneous fat (mm)



Hong, SK, DW Rennie, YS Park (1986)

Diurnal changes in oral temperature of the Korean diving women during various seasons of the year in relation to the diving work.

PHYSIOLOGICAL AND THERMAL RESPONSES OF MALES WITH VARYING BODY COMPOSITION DURING IMMERSION IN MODERATELY COLD WATER

E Glickman-Weiss, FL Goss, RJ Robertson, KF Metz, DA Cassinelli

Aviat Sp Environ Med (1991) 92:1063-7

Subject Characteristics

Variable	Low Fat (n = 12) $\bar{X}$ (±S.D.)	High Fat (n = 12) $\bar{X}$ (±S.D.)
Percent Fat	10.29 (1.44)	19.79 (2.14)
Sum of Skinfolds (mm)*	77.24 (20.85)	131.06 (40.23)
Weight (kg)	80.69 (12.04)	84.90 (15.02)
Height (cm)	181.03 (6.85)	177.48 (7.43)
Age (year)	24.75 (4.07)	30.00 (5.22)
Surface Area: Mass Ratio ($cm^2 \cdot kg^{-1} \cdot 100$)	2.01 (0.17)	2.02 (0.20)

* Sum of skinfolds include: chin, subscapula, chest, suprailium, triceps, thigh, biceps, forearm, knee, side and calf.

TABLE II. BODY COMPOSITION AND DISTRIBUTION ACROSS EXPERIMENTAL CONDITIONS OF SUBJECTS COMPLETING 90 MIN OF COLD WATER IMMERSION.

	Water Temperature		
	18°C	22°C	26°C
Low Fat (n = 12)	$\bar{X}$ = 11.51 S.D. = 1.08 n = 4	$\bar{X}$ = 9.53 S.D. = 1.25 n = 4	$\bar{X}$ = 9.83 S.D. = 1.44 n = 4
High Fat (n = 12)	$\bar{X}$ = 18.18 S.D. = 0.69 n = 4	$\bar{X}$ = 19.72 S.D. = 2.55 n = 4	$\bar{X}$ = 21.48 S.D. = 1.60 n = 4

TABLE III. MEANS AND STANDARD DEVIATIONS FOR RECTAL TEMPERATURE (°C).

Temperature (°C) Immersion time (min)	Low Fat		High Fat	
	Mean	±S.D.	Mean	±S.D.
18°C				
0*	37.2	0.2	37.4	0.2
5	37.1	0.3	37.3	0.2
15	37.0	0.3	37.2	0.2
30	36.8	0.5	37.0	0.2
45	36.6	0.6	36.8	0.4
60	36.4	0.7	36.5	0.5
75	36.1	0.7	36.4	0.4
90	35.9	0.8	36.2	0.4

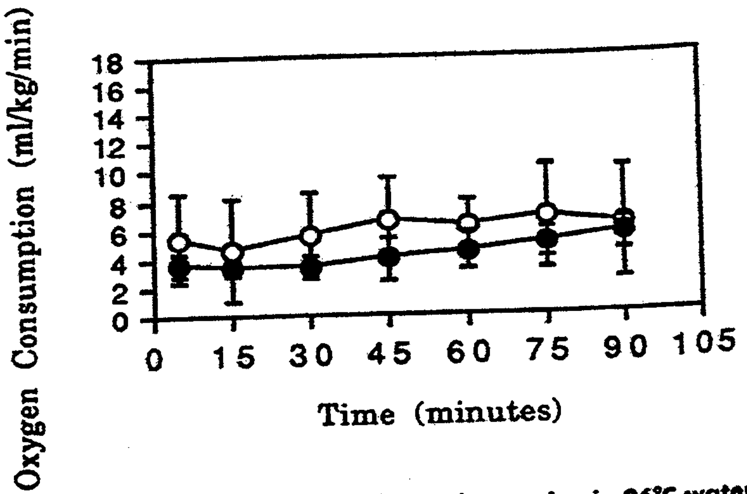


Fig. 1. Oxygen consumption during immersion in 26°C water. Open circles (○) = low fat; closed circles (●) = high fat individuals.

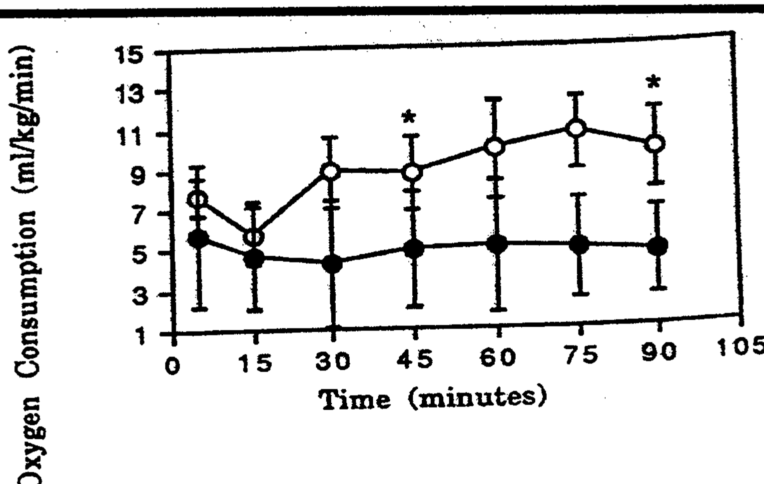


Fig. 2. Oxygen consumption during immersion in 22°C water; *$p < 0.05$. Open circles (○) = low fat; closed circles (●) = high fat individuals.

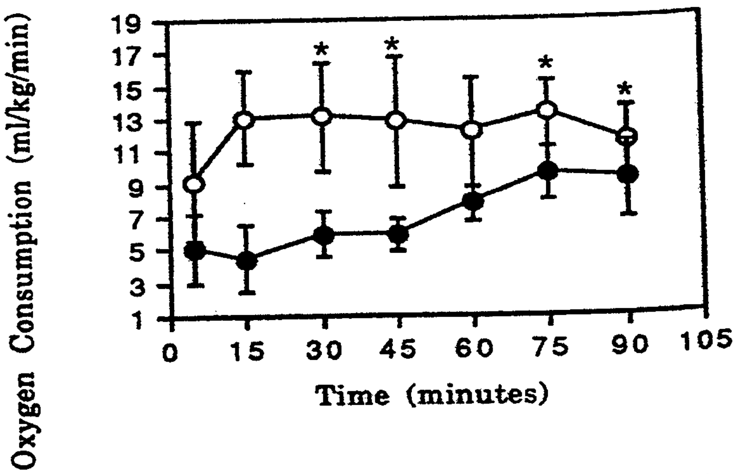


Fig. 3. Oxygen consumption during immersion in 18°C water; $*p < 0.05$. Open circles (○) = low fat; closed circles (●) = high fat individuals.

Conclusion

- **The fixed resistor to heat exchange (i.e., body fat) plays an important role in the thermoregulatory and aerobic metabolic responses to protracted resting cold water immersion.**
- **Although at a marked disadvantage, given the smaller resistive component to heat exchange, the LF (low fat) group was able to maintain Tre when compared to the HF (high fat) group, due, in part, to a significantly greater aerobic heat production through shivering thermogenesis.**

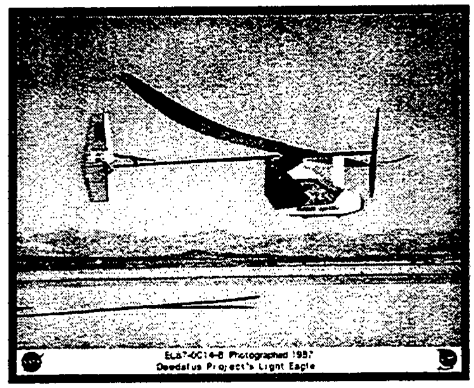
Human Powered Systems
The Daedalus Project

Mythical Greek inventor: constructed wings of wax/feathers, flew from imprisonment on Crete 3500 years ago

Route 119 km

3x human-powered flight of 35 km (1979 English Channel)

Nadel, ER and Bussolari, SR.
American Scientist, 1988.



The Daedalus Project

Question

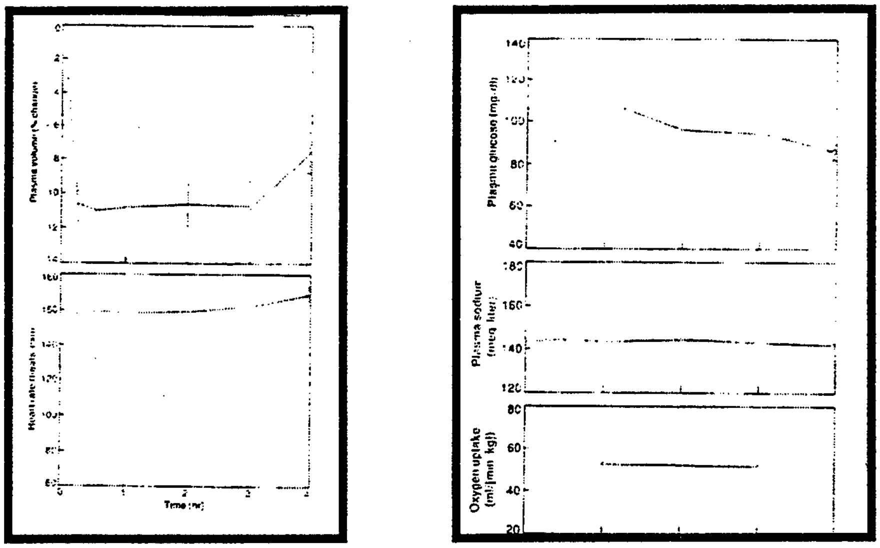
VO_2max requirement to perform 4-6 hours of flight?

Metabolic cost to the pilot of maintaining the constant mechanical power?

Answer

69.9 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$

The Daedalus Project (Endurance Test)



The Daedalus Project (Endurance Test)

The results of a 4 hour endurance test indicated that the Daedalus flight was physiologically possible

11 Athletes at 70% VO_2max

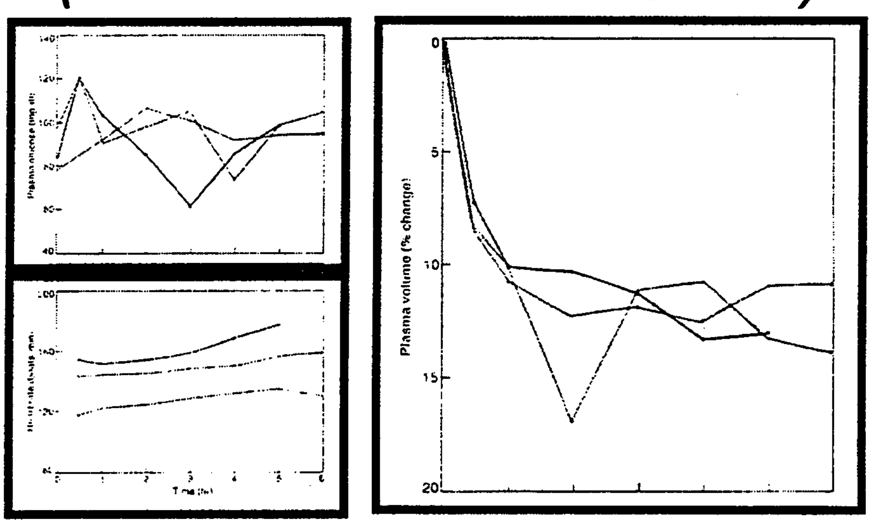
The Daedalus Project (Daedalus Drink)

(1L / hr)

- Maintain Tre
- Sufficient
  - carbohydrates
  - electrolytes
  - glucose
  - sodium
- Total Body Water

Kent

The Daedalus Project (Effectiveness of Daedalus Drink)



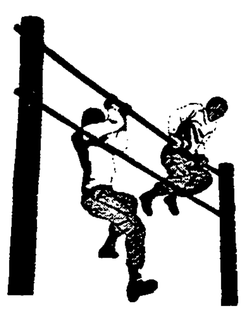
The Daedalus Project Postscript

- 23 April 1988, the Daedalus lifted off
- 4 hours and 119 km later Daedalus made a water landing into a 12 knot headwind
- Pilot Kanellos Kanellopoulous
  - Consumed 4 L energy electrolyte
  - HR $\leq$ 142 bpm
  - No indication of impending fatigue

Kent

PHYSIOLOGICAL FACTORS THAT MAY LIMIT AND TECHNIQUES THAT MAY ENHANCE HUMAN PERFORMANCE

E. Glickman-Weiss, PhD, FACSM



Exercise Sciences Laboratory

Kent State University

November 2, 1997

TECHNOLOGY SESSION 1

“ELECTROSTATIC INTEGRATED FORCE ARRAYS”

Dr. Scott H. Goodwin-Johansson

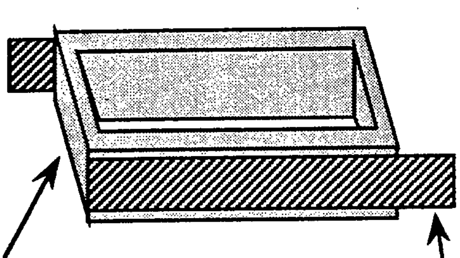
MCNC
Research Triangle Park, NC 27709

Integrated Force Arrays

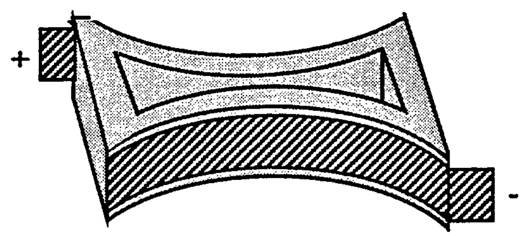
Scott Goodwin-Johansson

ELECTRONIC TECHNOLOGIES DIVISION
MCNC

IFA Operation



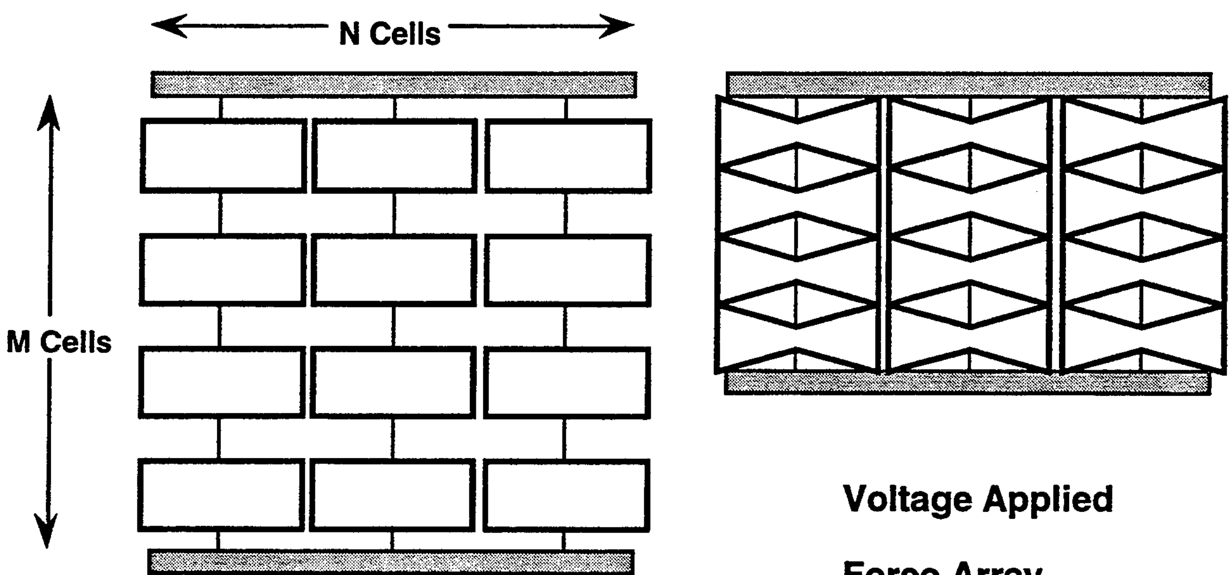
Force Cell



Voltage Applied

Electrostatic Attractive Force

IFA Operation



Voltage Applied

Force Array

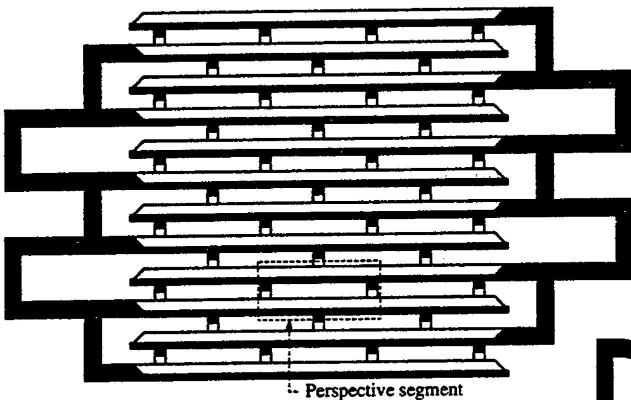
Total Force = N X Cell Force

Total Displacement = M X Cell Displacement

Force of Individual Cell is Independent of Size

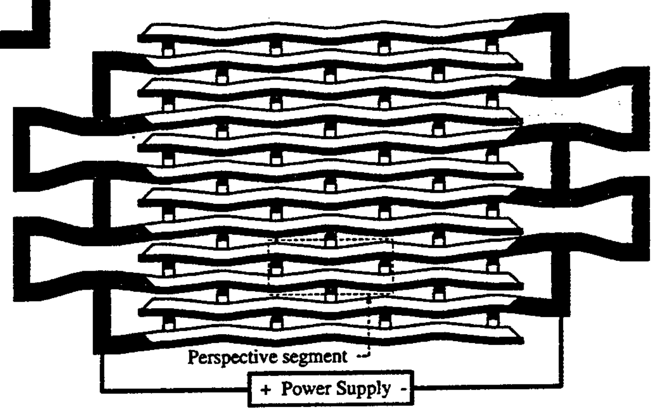
INTEGRATED FORCE ARRAYS

IFA Structure

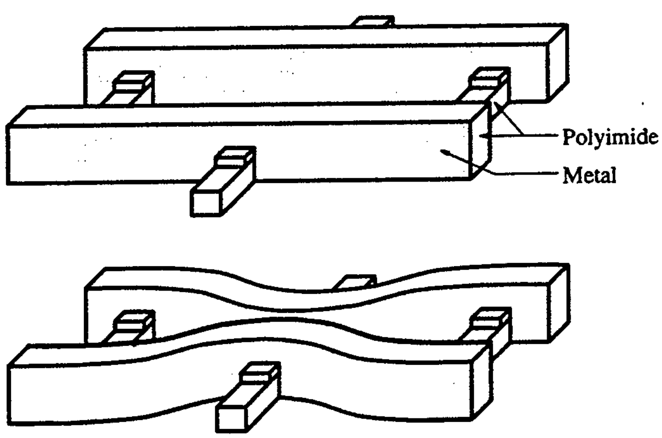


Relaxed

Compressed



Unit cell



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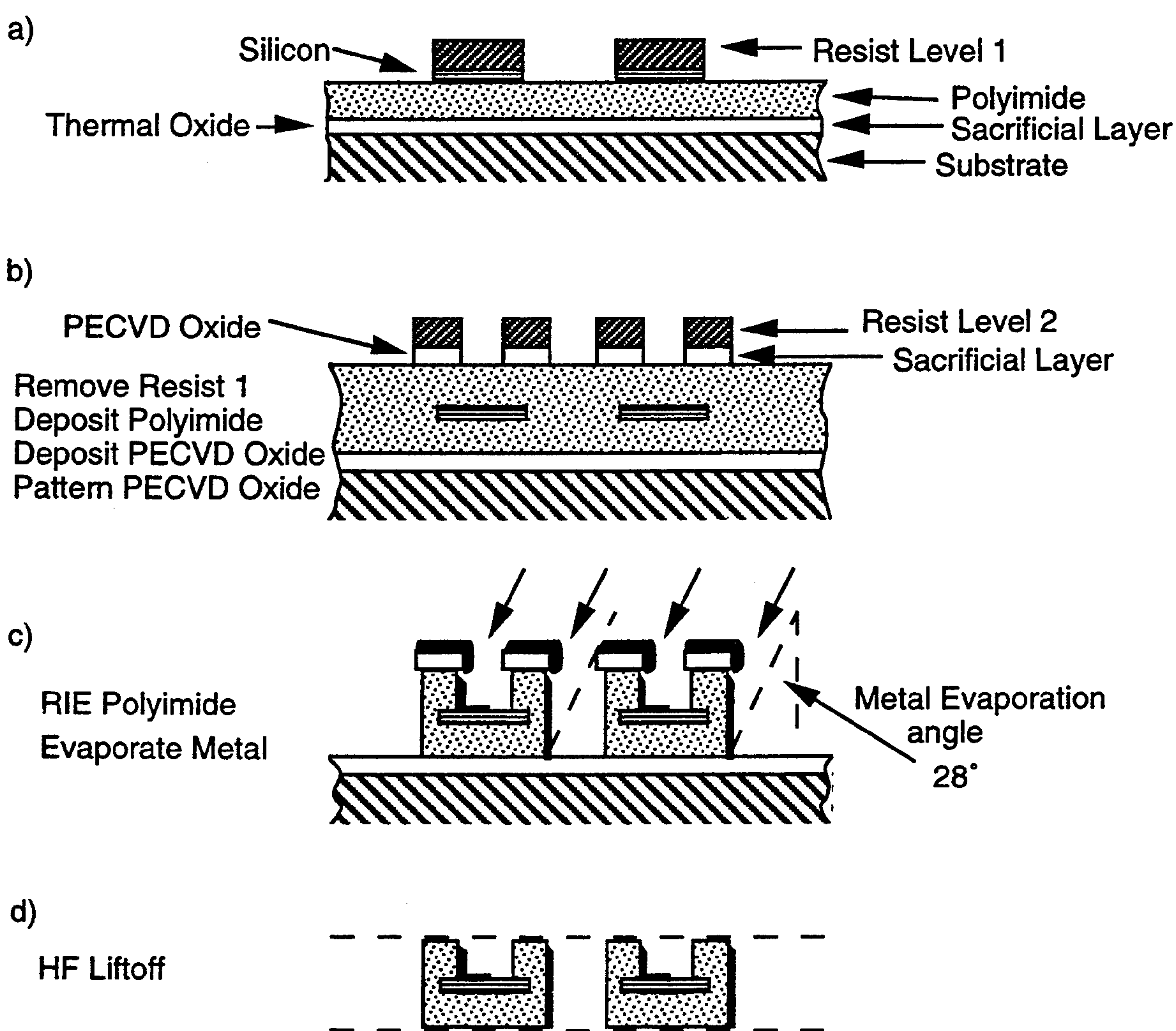
ELECTRONIC TECHNOLOGIES DIVISION

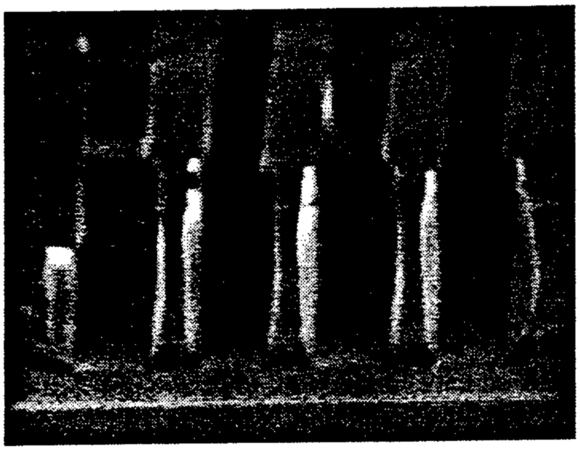
IFA Fabrication

Embedded Hard Mask



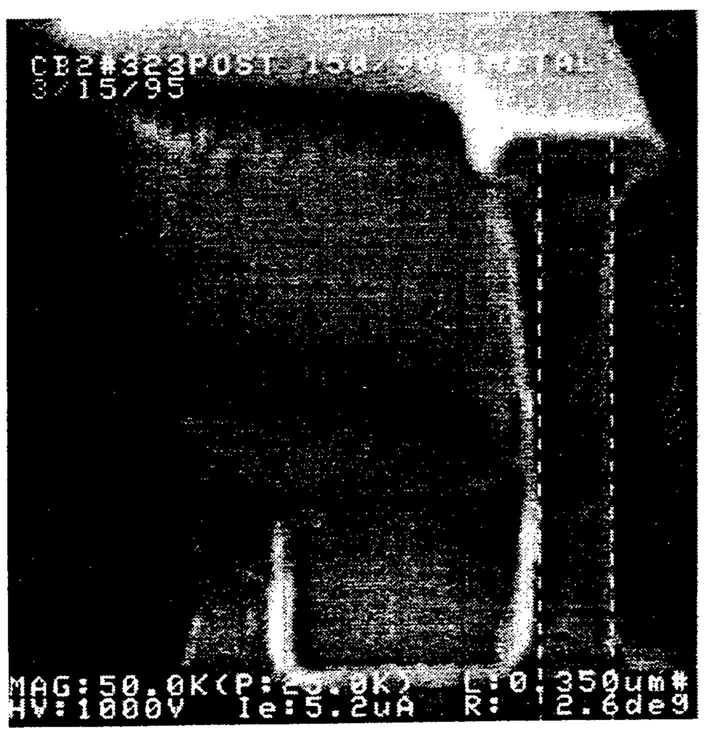
INTEGRATED FORCE ARRAYS

IFA Structure



Dual Surface
Hard Mask

Embedded
Hard Mask



ELECTRONIC TECHNOLOGIES DIVISION

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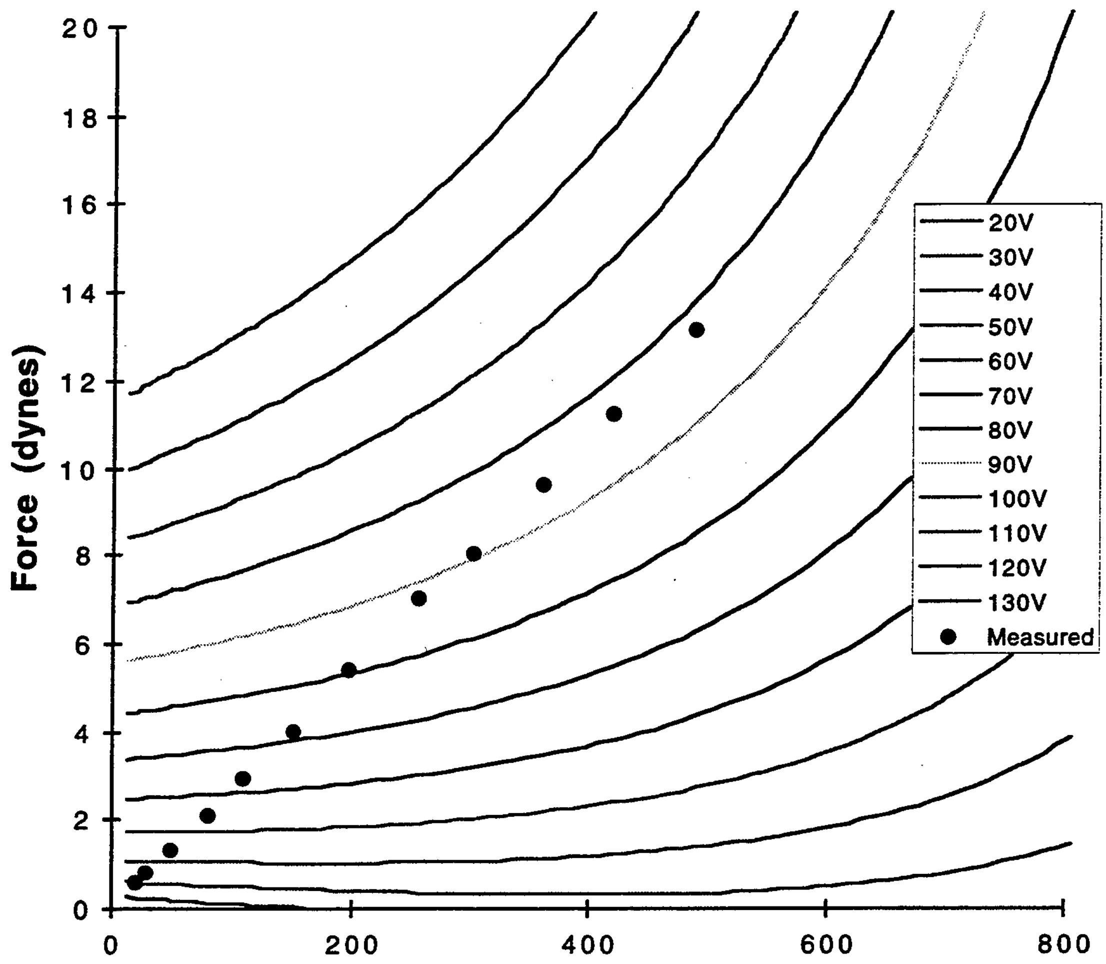
IFA Characteristics

- Artificial muscle
- Light-weight, flexible, electrostatic actuator
- Low Power
- Large displacements
  - 20% contraction of actuator length
- Large forces
  - Measured work/volume > 15 ergs/mm^3
- High speed
  - >20,000 contractions per second
- Reliable
  - Measured lifetimes >10^8 contractions

INTEGRATED FORCE ARRAYS

Measured Force

Theoretical curves and measured data points as a function of the applied voltage



Measured data in 10V increments beginning at 20V

MCNC ELECTRONIC TECHNOLOGIES DIVISION

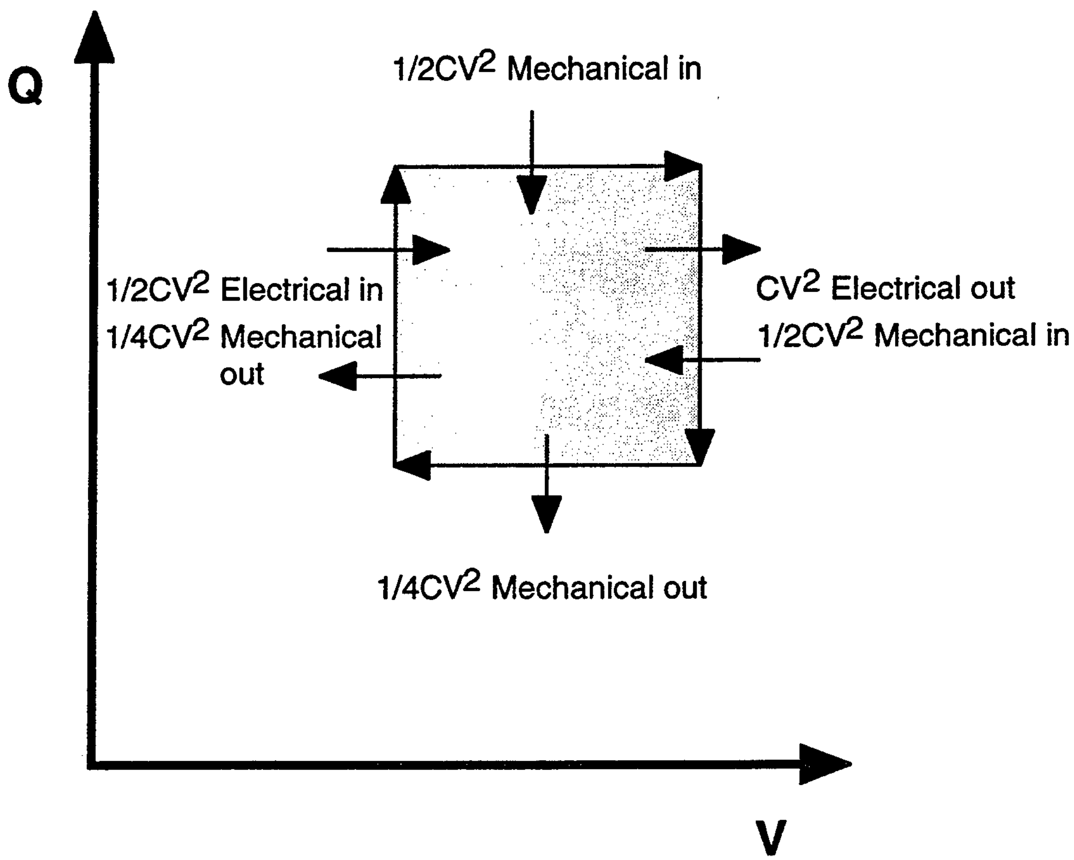
IFA Applications

- Small, fast actuators
  - Positioning of magnetic disk drive read heads
  - Optical shutters
- Mechanical actuation
  - Replace electromagnetic solenoids with 5% the volume and 0.6% the mass
  - Robotics
- Biomechanics and biomedical devices
  - Prosthetic devices
  - Catheter steering
- Sensors
- Power generation

IFA Power Generation

- Convert mechanical work into electrical energy
- Operate in an energy cycle
- 218cm^3 IFA generates 1W
  - 1Hz cycle
  - Maximum voltage 100V
  - 1.7μm plate pitch
  - 50% efficiency

IFA Power Cycle



Outstanding Issues

- Verify operation
- Optimize structure
- Fabrication of larger structures
- Low cost fabrication methods

Conclusions

- The concept of the IFA has been experimentally verified
- IFAs are low power, low weight, flexible actuators
- Good measured actuator performance characteristics
- IFA can be operated to convert mechanical work into electrical energy

"ENERGY CONSERVATION AND ALTERNATIVE ENERGY SOURCES FOR WEARABLE ELECTRONICS"

Dr. Daniel P. Siewiorek

Carnegie Mellon University
Pittsburgh, PA 15213-3890

Energy Conservation and Alternative Energy Sources for Wearable Electronics

November 3, 1997

by
Daniel P. Siewiorek

DARPA

Conservation vs Generation

- Reduce consumption by adapting design to application
- On demand or continuous

Time Rate of Change of Energy Consumption

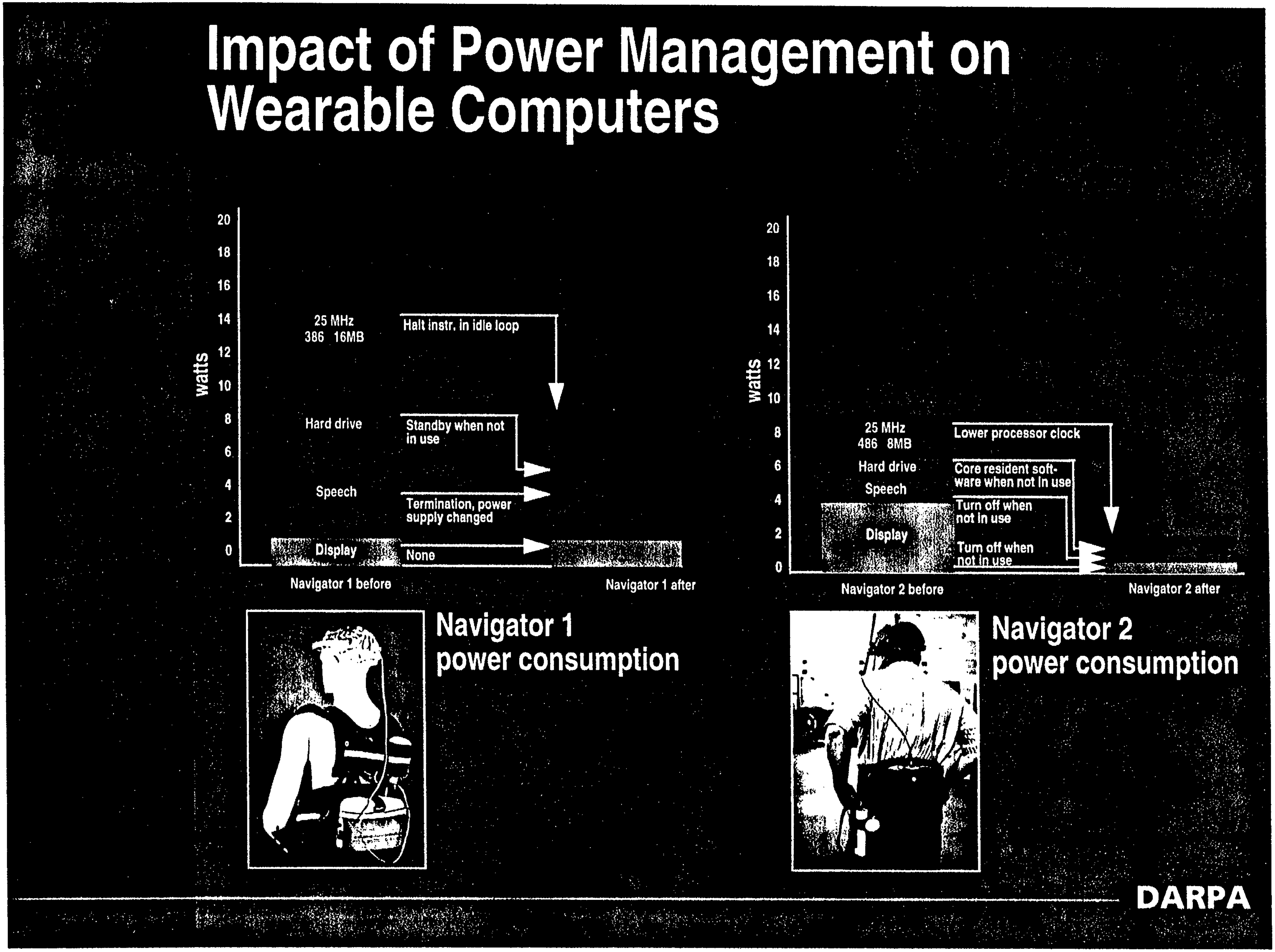
Fraction of System Power	1993	1995	2001
Computer	63%	29%	10%
Display	19%	29%	10%
Radio	18%	43%	80%
Total	33W	9W	2W

Conservation Techniques

- Operating System. "Idle" loop. Unused functionality
- Disk Drive. Load and execute. Modify usage pattern to take advantage of technology differences (i.e. magnetic spinning disk vs solid state)

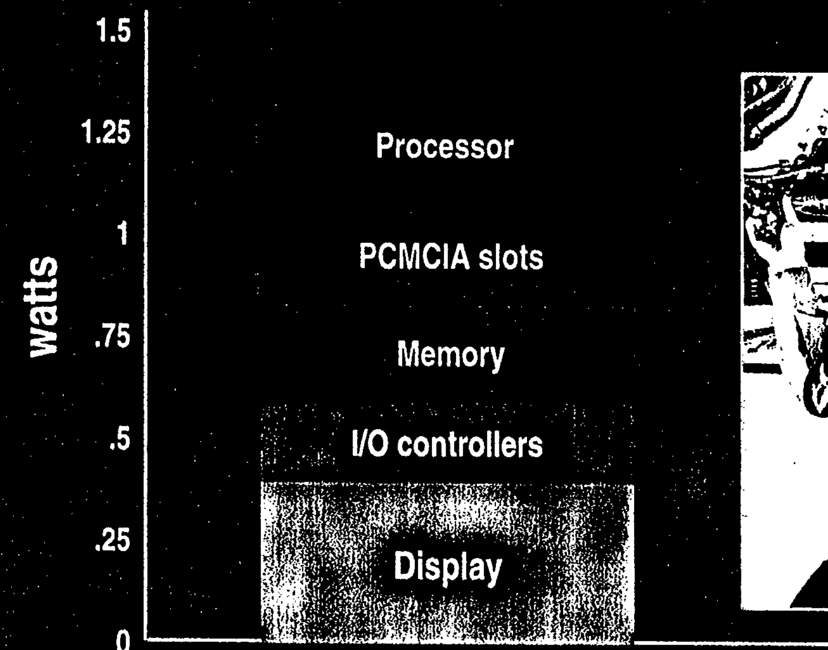
Conservation Techniques (continued)

- Hardware. Remove unused components. Adjust clock frequency to demands of application. Sensors to enable circuits on demand (e.g. display, "onset of speech")



Impact of Power Management on Wearable Computers
watts
20
18
16
14
12
10
8
6
4
2
0
25 MHz
386 16MB
Halt instr. in idle loop
Hard drive
Standby when not in use
Speech
Termination, power supply changed
Display
None
Navigator 1 before
Navigator 1 after
Navigator 1 power consumption
watts
20
18
16
14
12
10
8
6
4
2
0
25 MHz
486 8MB
Lower processor clock
Hard drive
Core resident software when not in use
Speech
Turn off when not in use
Display
Turn off when not in use
Navigator 2 before
Navigator 2 after
Navigator 2 power consumption
DARPA

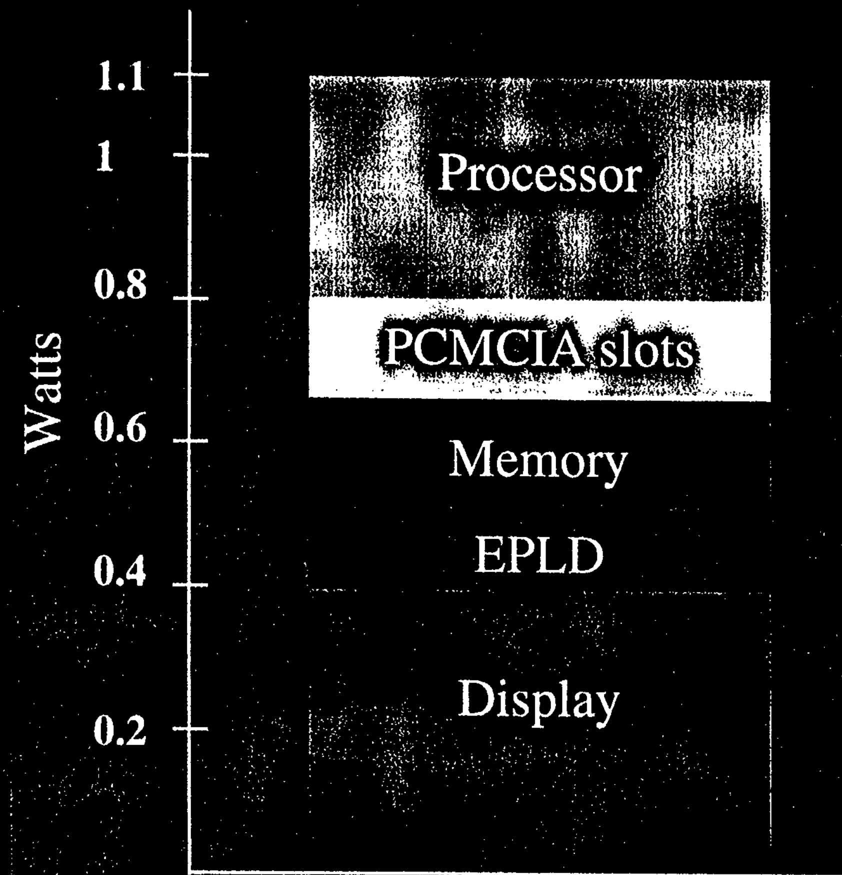
Power Consumption in a Dedicated Wearable Computers



Vu Man 3 power consumption

DARPA

Power Consumption Profile for VuMan2



Vu Man 2 Power Consumption

DARPA

Generation

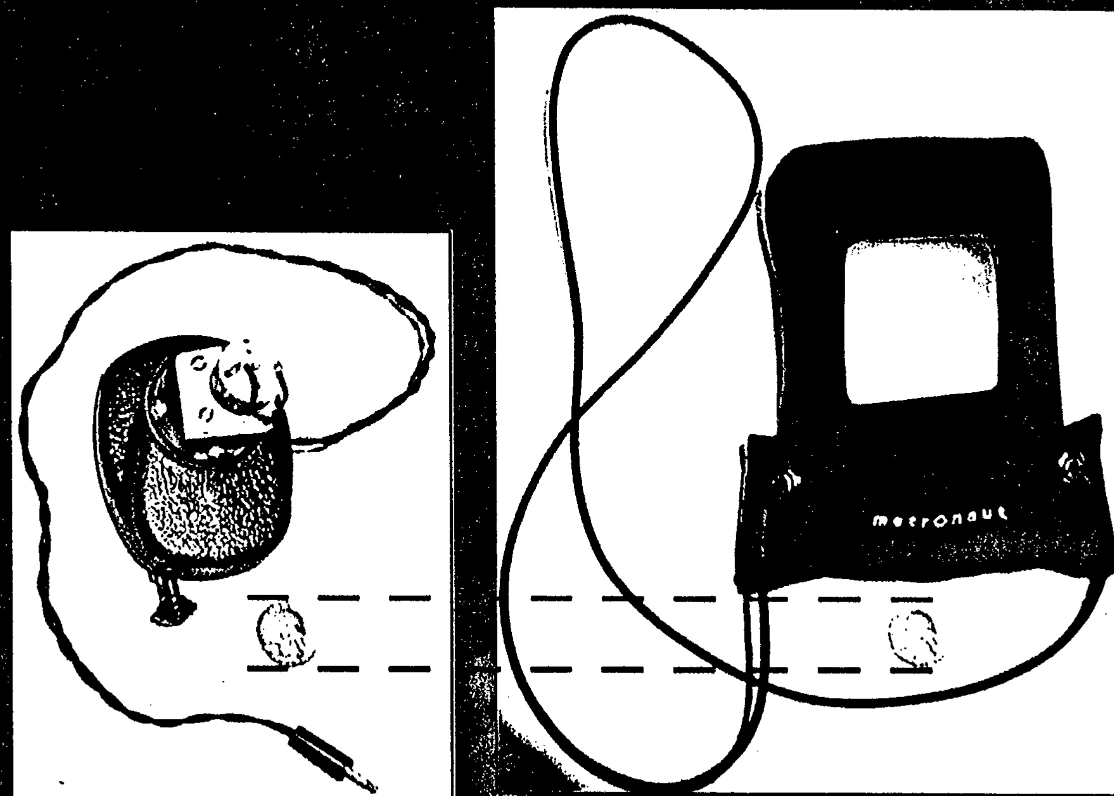
On Demand

- Fly wheel/generator
- Chemical
  - gas generation
  - electrochemical reaction
- Kinetic
  - electrical induction

Continuous

- Piezoelectric electromechanical couplers

On Demand Electro/Mechanical Energy Generator



DARPA

“ENERGY STORAGE/CONVERSION MATERIALS”

Dr. Ralph Zee

Materials Research and Education Center
Auburn University, AL 36849

Power Generation based on Piezoelectricity

Ralph Zee
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Summary

There are different means to conversion mechanical energy from human motion into electrical energy. A significant amount of energy is dissipated by the walking (and running) motion of a person. Early development of this type of materials concentrated on ceramic materials such as PZT (lead zirconate titanate) and $BaTiO_3$. The use of piezoelectric materials has significant increased in the advent of piezoelectric polymers, such as polyvinylidene fluoride (PVDF) in 1969. The flexibility, ductility, low cost and high conversion efficiency of these polymers compared to traditional piezoelectric ceramics have greatly enhanced the commercial applications of this class of materials. Numerous companies have been formed dedicated to the promotion, development and sales of these materials (such as AMP Inc.). Much of the effort has been devoted to the use of piezoelectric materials as sensors and transducers and even actuators. For example, devices based on PVDF have been developed as frequency counter, impact monitor, contactless keyboards, echo pulse sensors, sheet speakers, wear indicators, just to name a few.

The area of piezoelectric materials that has not been extensively explored is the generation of electrical energy from mechanical deformation of the piezoelectric process. In recent years, athletic shoe companies have incorporated piezoelectric films in the sole to convert mechanical energy into electricity to activate warning lights for night joggers. Medical researchers have attempted to use PVDF to generate power inside the body. PVDF has also been used as actuator switches using electricity generated by mechanical motion.

Content of the presentation will concentrate on the following topics:

(1) History and basic concept of the piezoelectric effect and piezoelectric materials,

(2) the governing equations for power generation using such a material,

(3) Feasibility, limitation of this conversion process and issues to be addressed.

Energy Conversion Using Piezoelectric Materials - *Fantasy or Reality?*

Ralph Zee
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Presented at the Prospector IX Workshop, Durham, NC
November 3, 1997

Background

What is piezoelectricity?
Mechanical deformation ↔ Electricity
Requires ferroelectric materials.

Some history: Discovered 100 years ago by the Curie brothers
Piezo: Greek for "pressure, press".

What are some of the piezoelectric materials?
Ceramics: PZT (lead zirconate titanate)
Polymer: PVDF, Polyvinylidene fluoride, polarized fluoropolymer discovered in 1969 by Kawai.

What are piezoelectric materials commonly used for?
Sensors!!!!

Pros and Cons of Polymeric Piezoelectric Films

Pros	Cons
(1) Ease of fabrication. (2) Low costs. (3) Wide frequency response range: milliHz to GHz. (4) Large dynamic response range: 10^{-8} to 10^{6} psi. (5) High voltage output. (6) High mechanical strength and ductility. (7) Impact resistance. (8) High dielectric strength. (9) High electrical resistivity.	(1) Low temperature operation (100°C max) (2) Sensitive to electromagnetic radiation. (3) Relatively low dielectric constant (<100). (4) Relatively low capacitance. (5) Low electromechanical transmission. (6) High electrical resistivity.

Physical parameters of PVDF and PZT

Physical Properties	PVDF	PZT
Density (gm/cc)	1.78	7.5
Dielectric Constant	12	1,200
Max operating field (kV/mm)	10	0.3
Piezoelectric strain constant, d_{31} (10^{-12} C/N)	23	110
Piezoelectric strain constant, d_{33} (10^{-12} C/N)	36	250
Piezoelectric voltage constant, g_{31} (10^{-3} V-m/N)	216	10
Piezoelectric voltage constant, g_{33} (10^{-3} V-m/N)	339	25
Yield Stress (N/m^2)	4×10^8	5×10^7
Elongation at Yield (%)	3	0.08
Young's Modulus (N/m^2)	2.5×10^9	8×10^{10}
Tensile Strength at Break (N/m^2)	2×10^8	5×10^7
Elongation at Break (%)	27	0.08
Max operating temperature (°C)	100	150

Attempts to produce electricity from this stuff?

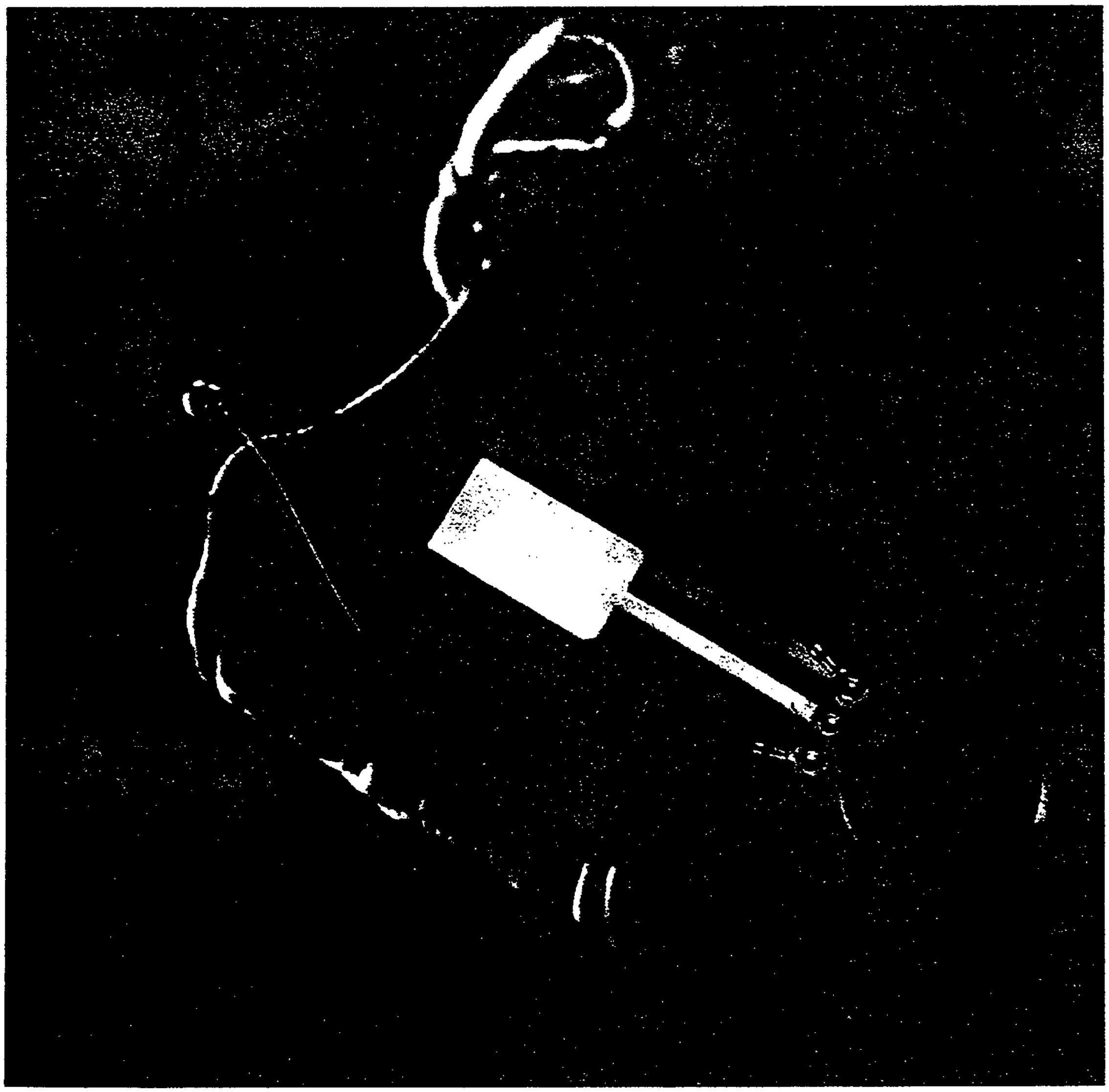
Sneakers?

Breathing action of human?

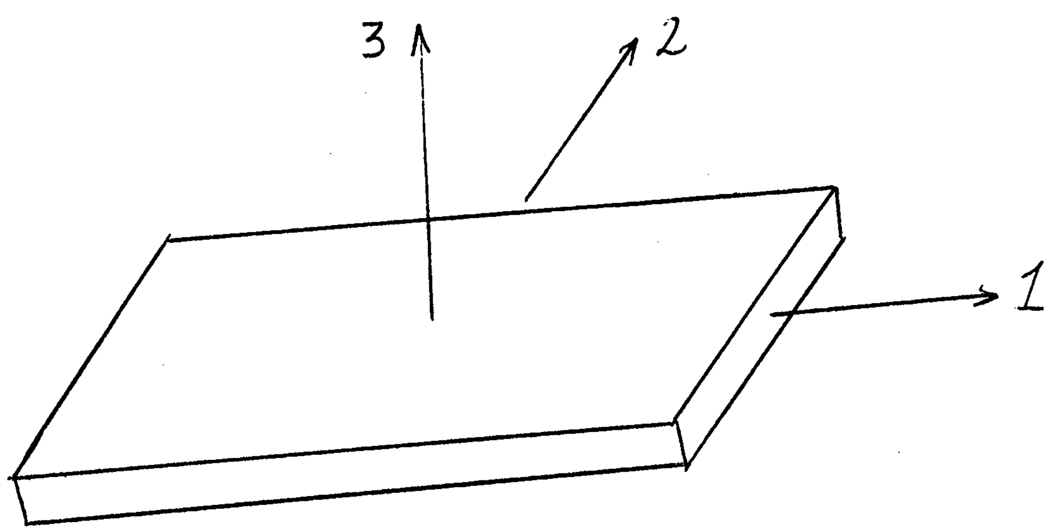
Heart motion?

Compression from bone joint? (17μW/joint obtained, estimated 10mW/gm possible)

What are the limits of this concept?



Two modes of operation for power conversion: Power generated in the thickness direction with stress applied in the same direction or along the length.



First Mode of Operation: 33 mode

$$Q = d_{33} A \sigma$$
$$V = g_{33} t \sigma$$

Q is the charge produced,
V is the voltage generated,
t and A are the thickness and the surface area of the film,
σ is the applied stress

$$E = \tfrac{1}{2} d_{33}\, g_{33}\, At\sigma^2$$

Using $A = 10\text{cm}^2$ and $t = 0.5\text{cm}$ (multilayer stacked together)
a walking rate of 1 step per second
force from a 180lb body giving a normal stress of $8\text{x}10^5$ N/m^2:

$$P = 0.02\text{mW}$$

Second Mode of Operation: 31 mode

$$Q = d_{31} A \sigma$$
$$V = g_{31} t \sigma$$

$$E = \tfrac{1}{2} d_{31}\, g_{31}\, A t \sigma^2$$

Using $A = 1.58\ cm^2$ and $t = 3.16\ cm$ (multilayer stacked together)
a walking rate of 1 step per second and
force from a 180lb body giving a normal stress of ***$5x10^6\ N/m^2$***:

$$P = 0.3\ mW$$

Theoretical Limit of Power Production

Yield stress is 5×10^8 N/m^2,   Yield strain is 3%

Assume applied stress is 40% of yield = 2×10^8 N/m^2 or 200 MPa

Mechanical Energy Available = $\frac{1}{2}\sigma\epsilon$ = 1000 kJ/m^3

Energy per activation (step) $= \frac{1}{2} d_{33}\, g_{33}\, At\sigma^2$ for the 33 mode

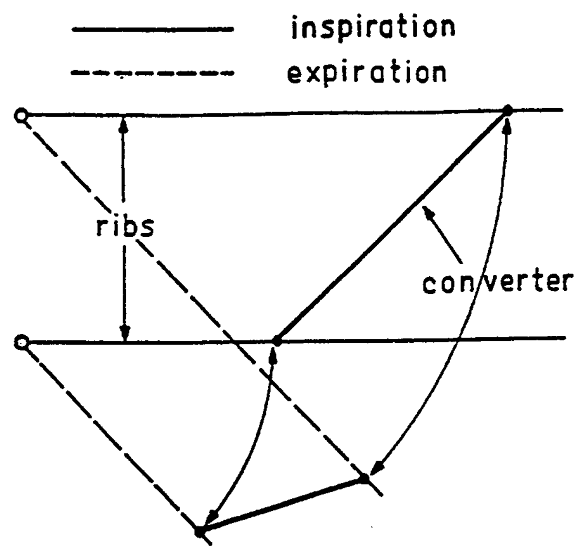
$= 240$kJ/m^3 or 0.24J/cm^3 or 0.13J/gm

Conversion Efficiency = 24%   for the 33 mode

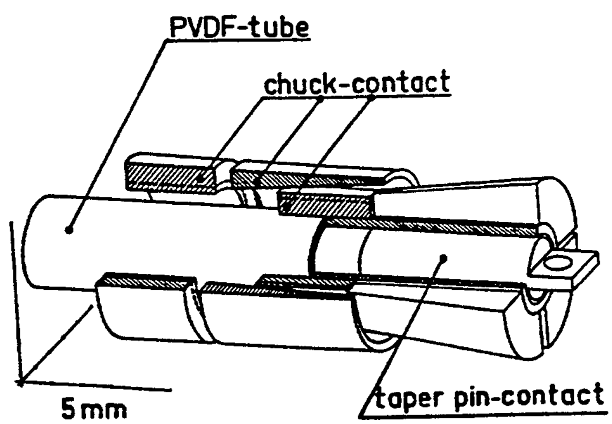
Energy per activation (step) $= \frac{1}{2} d_{31}\, g_{31}\, At\sigma^2$ for the 31 mode

$= 100$kJ/m^3 or 0.1J/cm^3 or 0.056J/gm

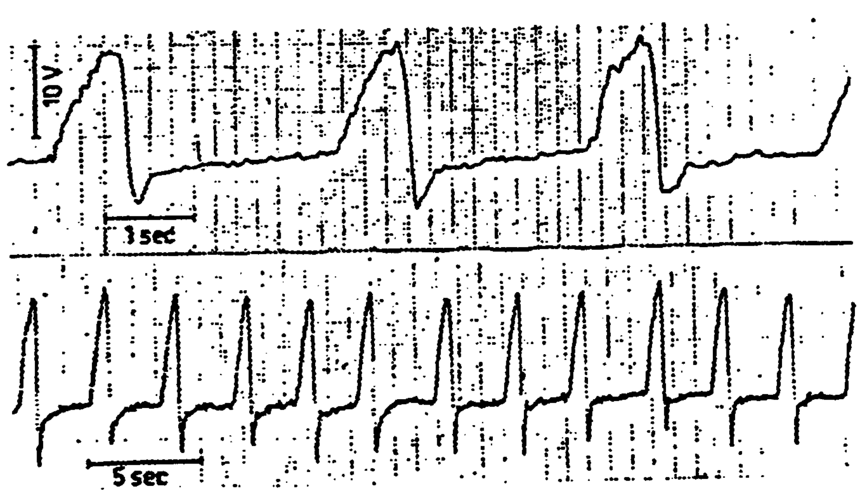
Conversion Efficiency = 10%   for the 31 mode



inspiration
expiration
ribs
converter



PVDF-tube
chuck-contact
5mm
taper pin-contact



10V
1 sec
5 sec

Issues to be addressed

(1) Efficiency is high.

(2) How does one generate the high stress needed?

(3) Work with the geometry due to the stress square dependence.

(4) Incorporation into human systems.

(5) Circuit design and power conditioning.

“ELECTROCHEMICAL CAPACITORS”

Dr. Stephen A. Merryman

Space Power Institute
Auburn University, AL 36849

Electrochemical Capacitors

Stephen A. Merryman
Auburn University

Presented at Prospector IX Workshop on
Human Powered Systems and Technologies
November 2-5, 1997
Durham, NC

Classification of Electrochemical Capacitors

★ By Electrode Type
- » Activated Carbon Powder
- » Carbon/Metal Fiber
- » Activated Synthetic Carbon
- » Doped Conducting Polymer Films on Carbon Cloth
- » Mixed Metal Oxides Deposited on Metal Foils

★ By Electrolyte Type
- » Aqueous
- » Organic
- » Solid

★ By Energy Storage Mechanism
- » Double Layer Capacitance
- » Psuedocapacitance

Key Capacitor Characteristics

★ Energy Density
  » Gravimetric
  » Volumetric

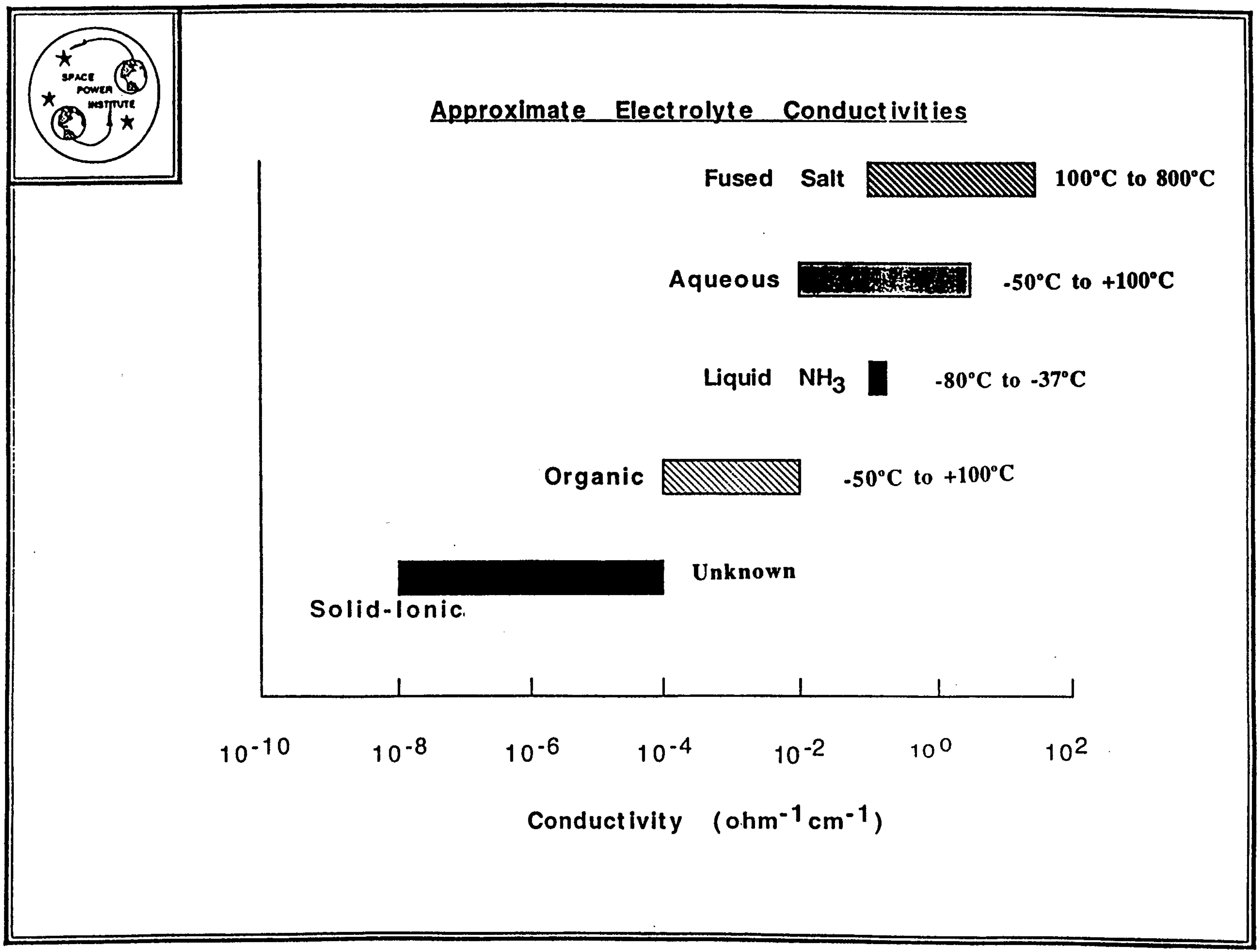
★ Capacitance Density
  » Gravimetric
  » Volumetric

★ Equivalent Series Resistance (ESR)

★ Equivalent Parallel Resistance (EPR)

Internal Resistance

- ★ Equivalent Series Resistance (ESR) determines the internal losses of the capacitor during cycling.
  - » Want ESR minimized
- ★ Equivalent Parallel Resistance (EPR) determines the leakage current or self-discharge of the capacitor.
  - » Want EPR to be large

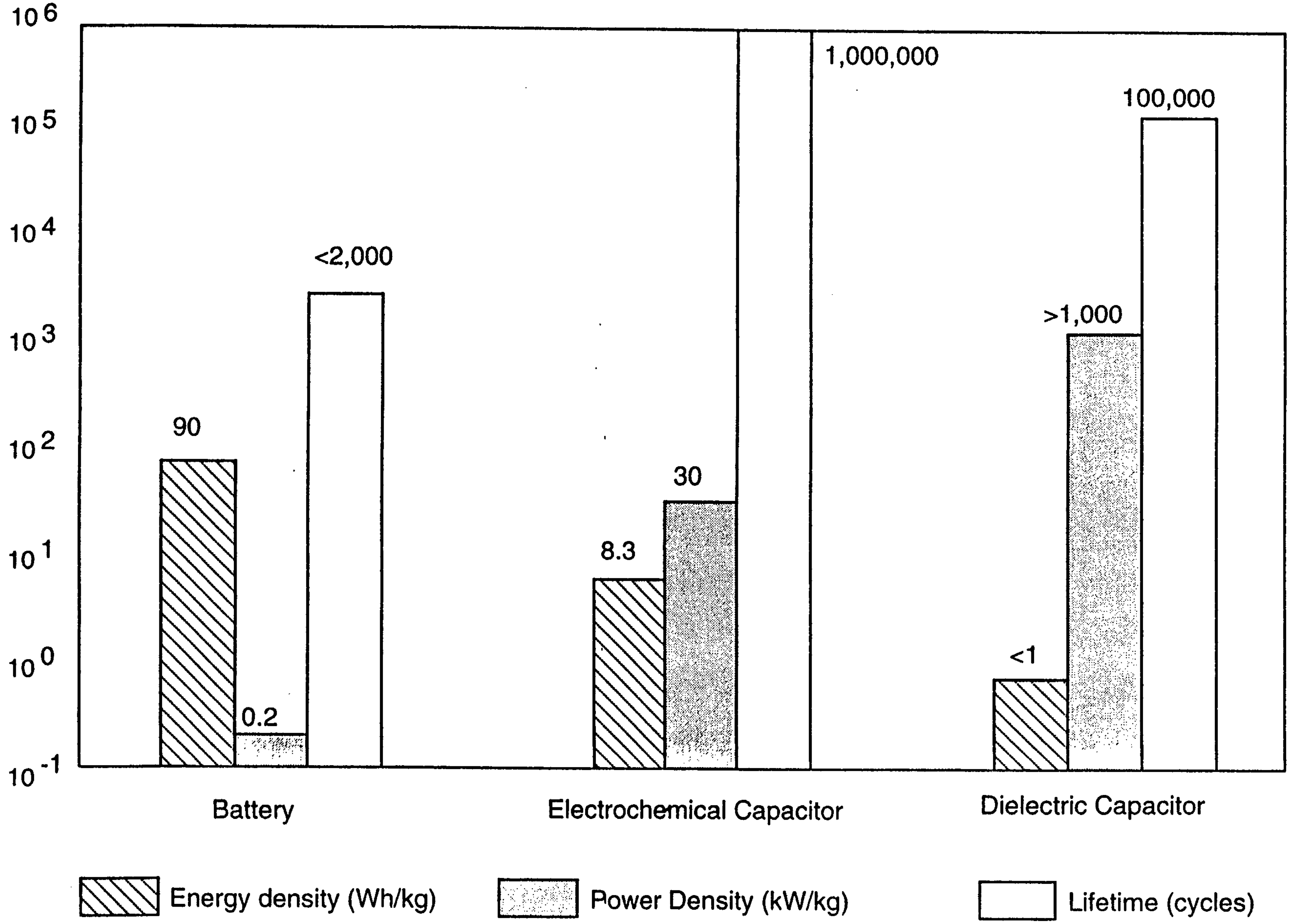


Approximate Electrolyte Conductivities
Fused Salt
100°C to 800°C
Aqueous
-50°C to +100°C
Liquid NH_3
-80°C to -37°C
Organic
-50°C to +100°C
Unknown
Solid-Ionic
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
Conductivity $(ohm^{-1} cm^{-1})$

Electrochemical Capacitors

* Highest demonstrated energy storage density for capacitive storage.
* Demonstrated power densities much greater than battery technologies.
* Greater than 1,000,000 charge/discharge cycles have been demonstrated.
* Exhibit non-explosive failure modes.
* Can be customized for a particular application.

Rechargeable Power Sources



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State-of-the-Art in Electrochemical Capacitors

STATE-OF-THE-ART ELECTROCHEMICAL CAPACITORS

	Capacitance (1) density (F/g)	Energy (2) density (Wh/kg)	Power (2) density (kW/kg)	Problems
DOE goal		>5	>1	
Carbon/aqueous	42	2.66	: 2.4	the operating voltage is low (0.6-0.8 V)
Carbon/organic	21	5.1	1.6	the ionic conductivity is low (< 30 mS/cm)
RuO_2 film	95	4.7	?	low package efficiency, high cost
$RuO_2.xH_2O$	192	8.3	> 30	high cost

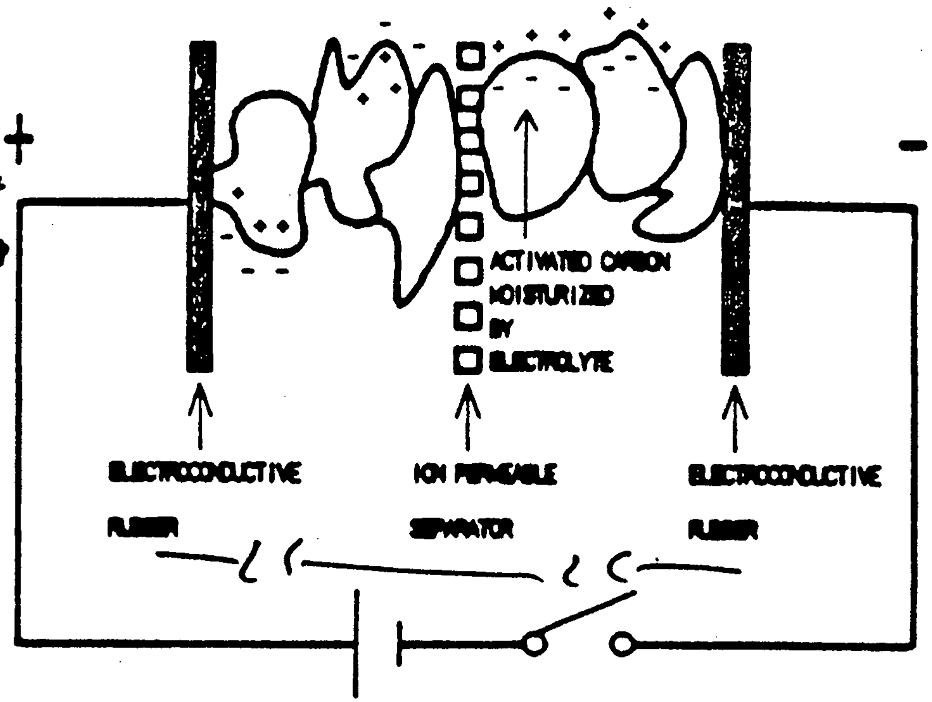
(1) only electrode material was counted.
(2) electrode and electrolyte were counted.

SPACE POWER INSTITUTE

Double Layer Capacitance

- ★ Helmholtz discovered that the interface between a conductor and electrolyte was capable of storing charge.
- ★ Layer is estimated to be approximately 10Å thick.
- ★ Use of large surface area materials (1500 m^2/g) enables multi-farad capacitors to be constructed.

CHEMICAL DOUBLE LAYER CAPACITOR
CARBON-AQUEOUS



$C = \epsilon \frac{A}{d}$ 1500 m² 10 Å

$$H_2SO_4 + H_2O \rightleftharpoons H_3O^{\oplus} + HSO_4^{\ominus}$$

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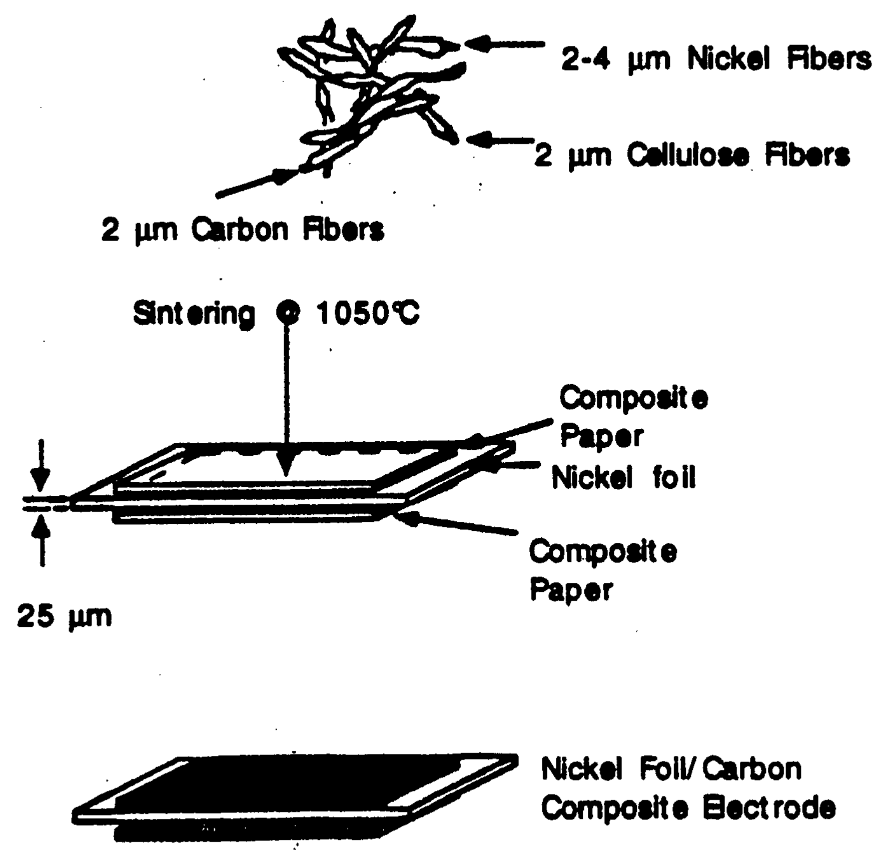
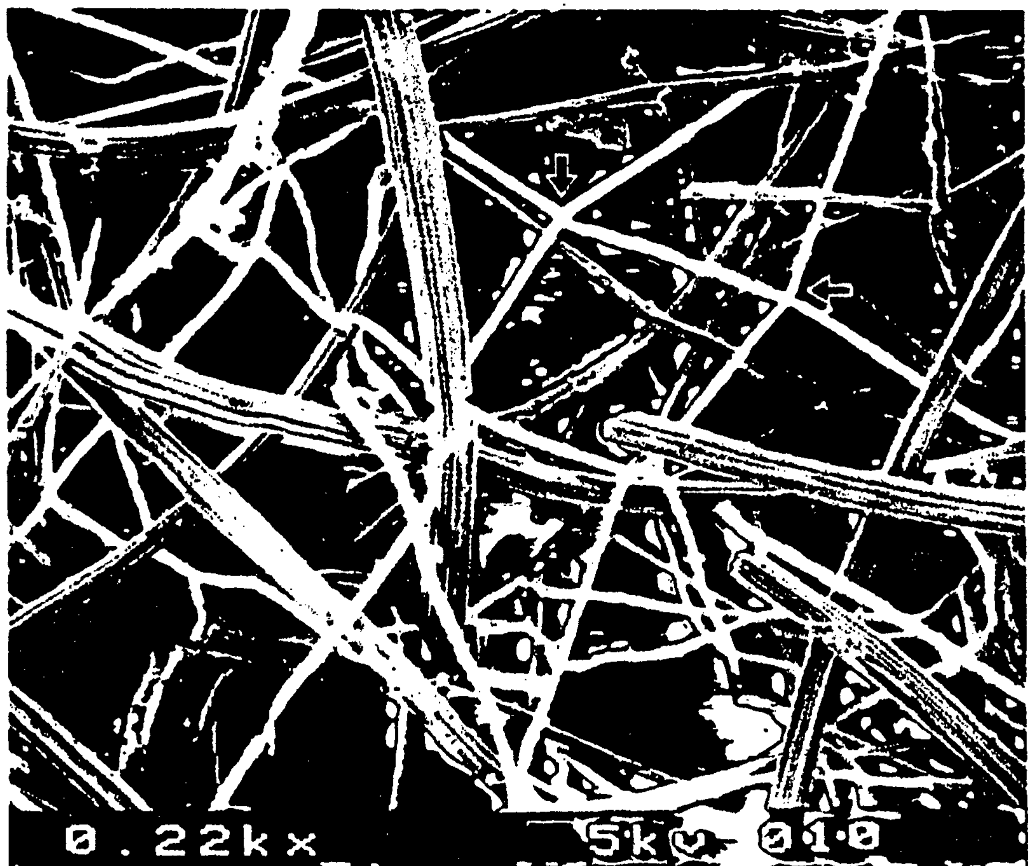
Composite Electrode Structure

- ★ Eliminate the need for pressure to obtain low values for the equivalent series resistance (ESR).
- ★ Uniform electrode structure using standard paper-making techniques with metal and carbon fibers with a cellulose binder.
- ★ Reaction sequence removes the binder while bonding the metal fibers and foil.

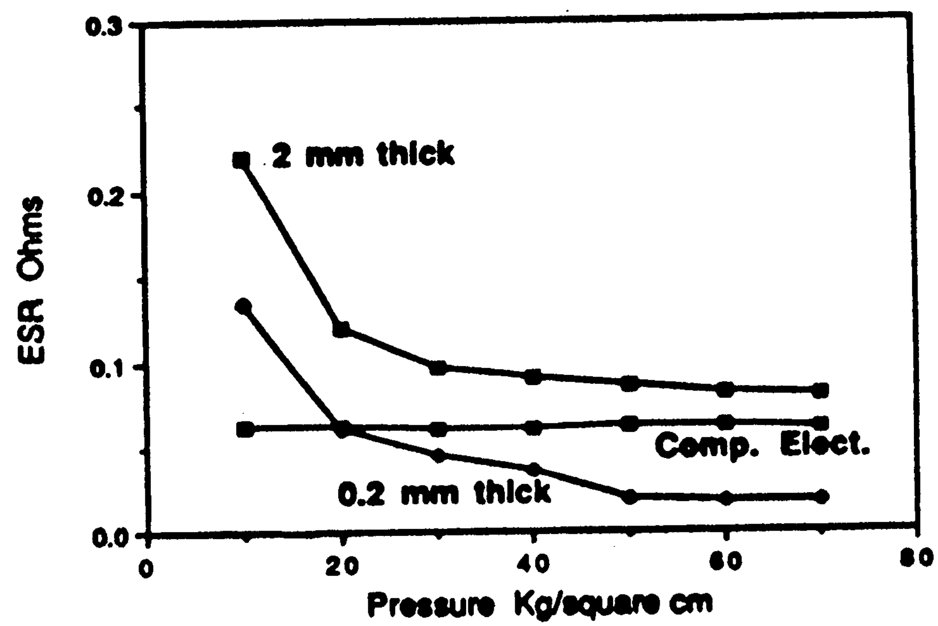
Composite Electrode Structure



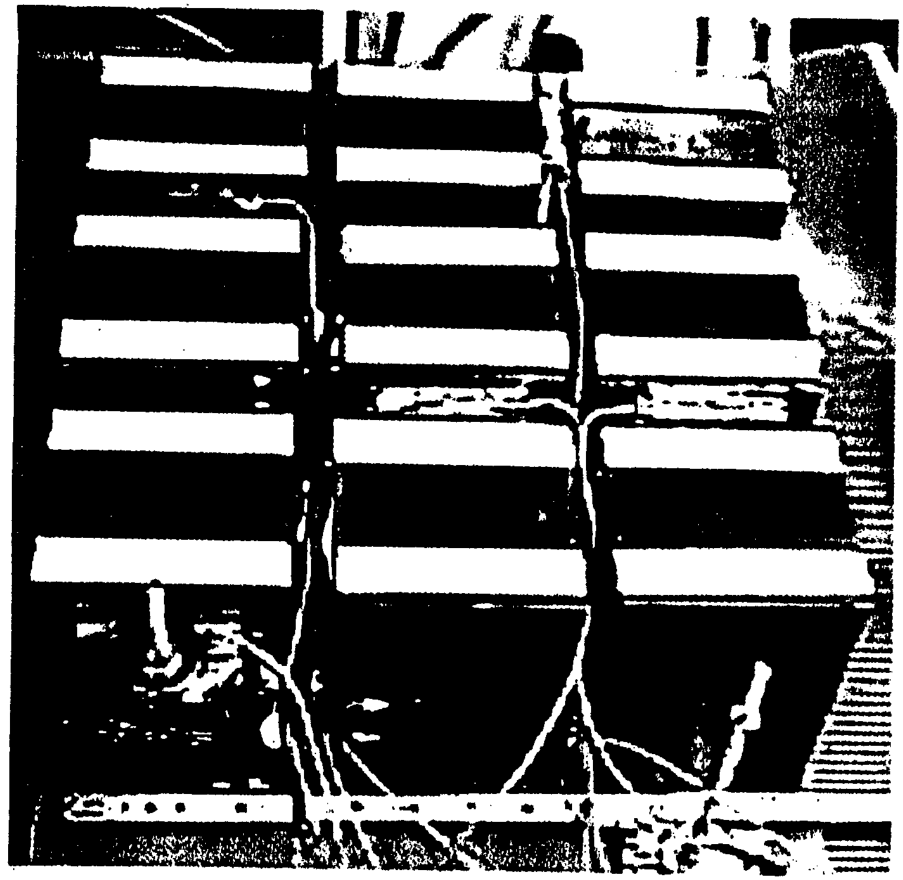
Composite Fiber Structure



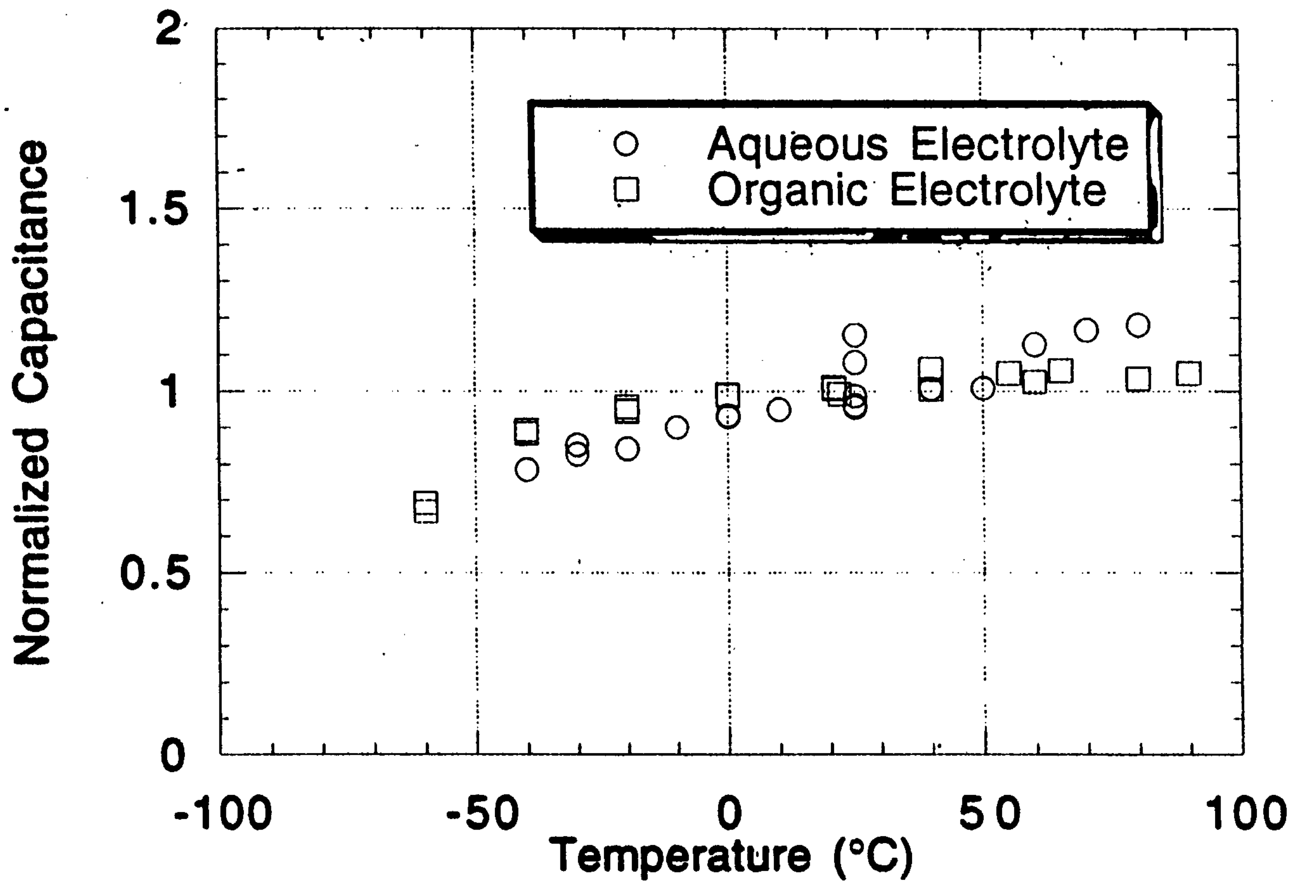
ESR Pressure Dependence



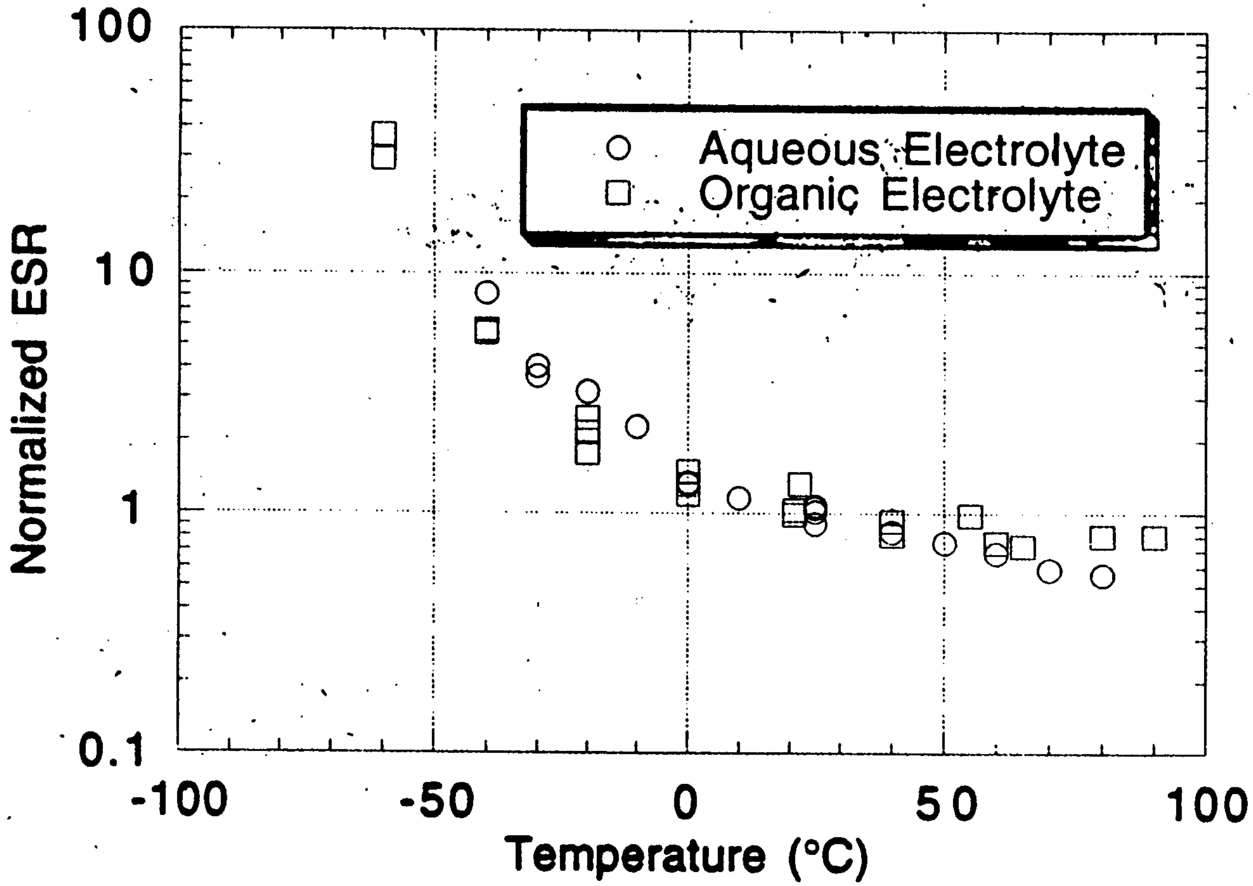
270-V, 0.8 F Capacitor Bank



Temperature Dependence



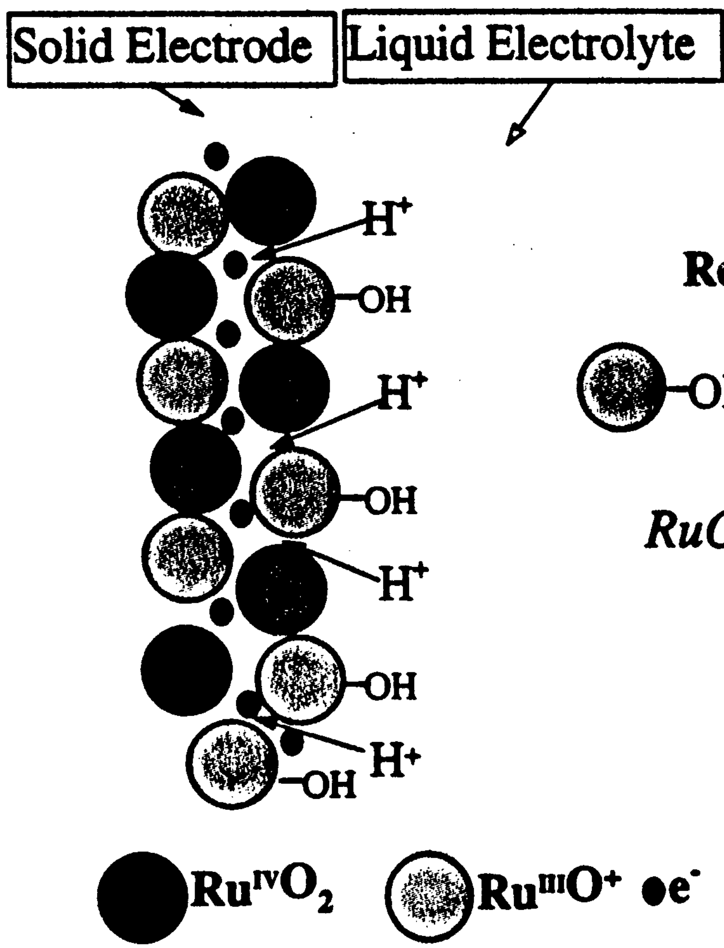
Temperature Dependence



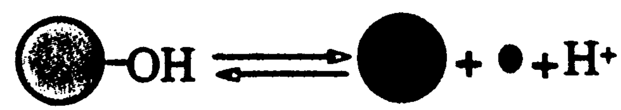
Psuedocapacitance

- ✶ Energy is stored electrochemically rather than electrostatically.
- ✶ Involves surface reactions with hydrogen ions and is essentially due to proton intercalation into the surface of the active material.
- ✶ Redox Reaction
  - $RuO(OH) \Leftrightarrow RuO_2 + H^+ + e^-$
- ✶ Much higher charge density than double layer capacitor.

Mechanism of Redox Capacitance of $RuO_2 \cdot H_2O$



Redox Reaction



$$RuO(OH) \Leftrightarrow RuO_2 + H^+ + e^-$$

Benefits:

*Volumetric redox
*Surface redox
*Surface double-layer

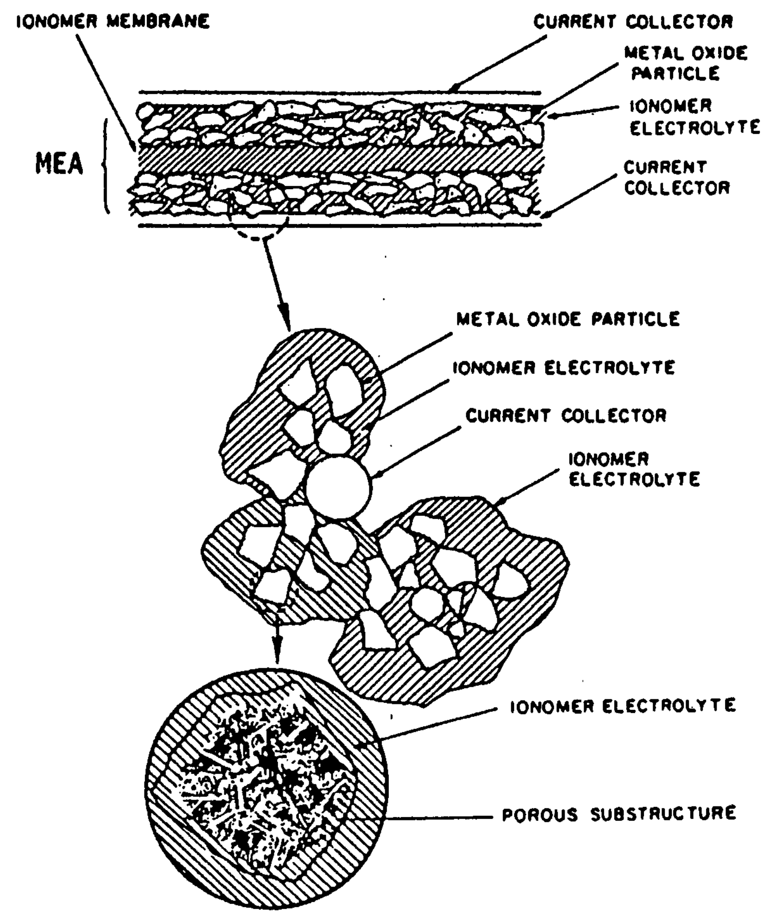
Key factors:

*Amorphous hydrated structure
*Sufficient protons
*Mixed ionic states, e.g. Ru^{III}, Ru^{IV}, etc.

Result:
Redox capacitor has 10 time higher storable charge-density than double-layer capacitor

PSEUDOCAPACITOR

METAL OXIDE WITH SOLID OR LIQUID ELECTROLYTE



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UNIQUE HYDRO-RUTHENIUM OXIDE CAPACITOR AND ITS COMPARISON

THE UNIQUENESS

* The Highest Specific Energy, 100 J/g
* Inexpensive Material Processing Technology
* Long Lifetime
* The Highest Specific Power, >30 kW/kg
* Using Well Established CDL Fabrication Technology
* Improved Frequency Dependence

COMPARISON

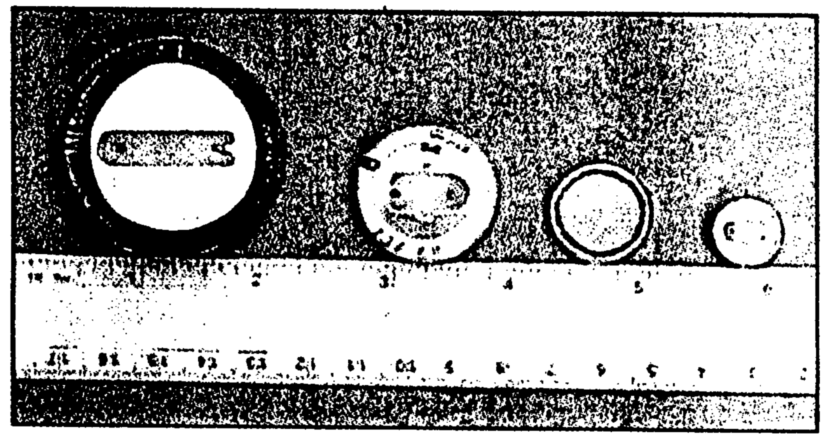
Capacitor	Electrolyte	Capacitance Density* F/g	Specific Capacitance F/g	Specific Energy** Wh/kg(J/g)	Specific Power** kW/kg
Activated Carbon	Organic	21	50	5.1(18.4)	1.6
Activated Carbon	Aqueous	42		2.7(9.7)	0.24
Crystal RuO_2	Aqueous	95	380	4.7(16.9)	
Amorphous RuO_2	Aqueous	195	1000	8.3(29.9)	>30

* Only electrode material was counted.

** Electrode and electrolyte were counted.

RuO_2 Supercapacitor Technology

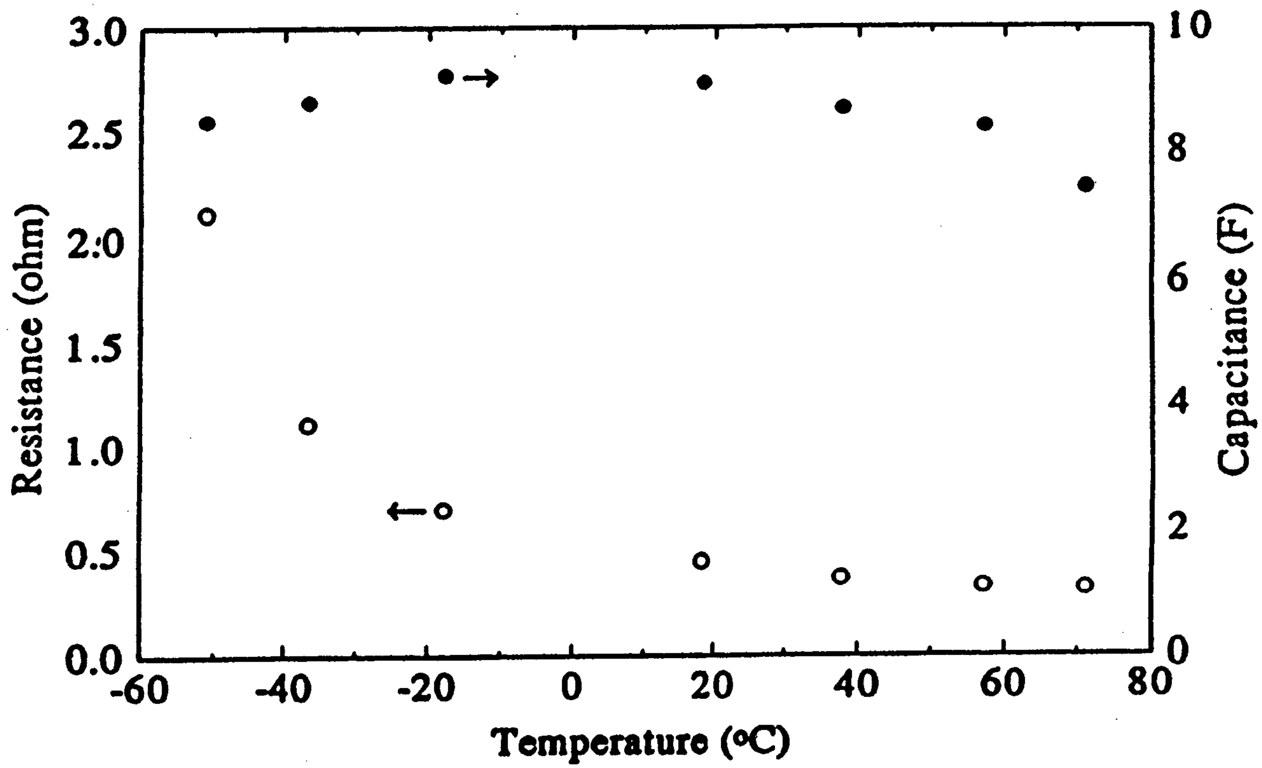
- ★ Hydrous RuO_2 chemistry
  - » With industrial partner
  - » Aqueous electrolyte
  - » Requires amorphous RuO_2
  - » Redox capacitance mechanism
- ★ Comparisons
  - » Specific capacitance: 1 F/mg (20x organic carbon)
  - » 30 j/g specific energy (3x aqueous carbon)
  - » >30 kW/kg specific power (100x aqueous carbon)
- ★ Processing
  - » Uses inexpensive CDL fabrication process



12.6 V	6.0 V	1.8 V	3.3 V
1.3 F	1.3 F	1.0 F	0.1 F

CSPAE

Capacitance (•) and ESR (∘) as Function of Temperature



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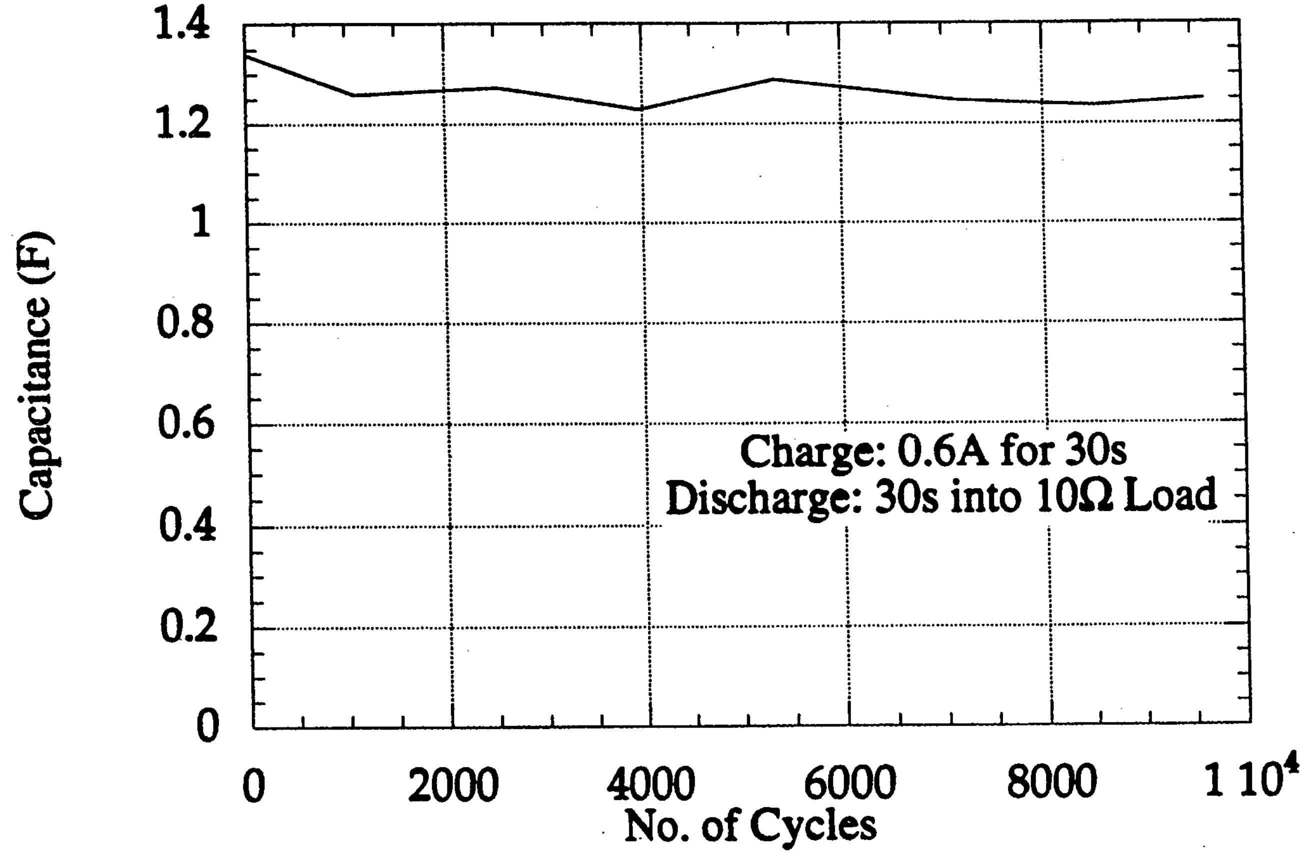
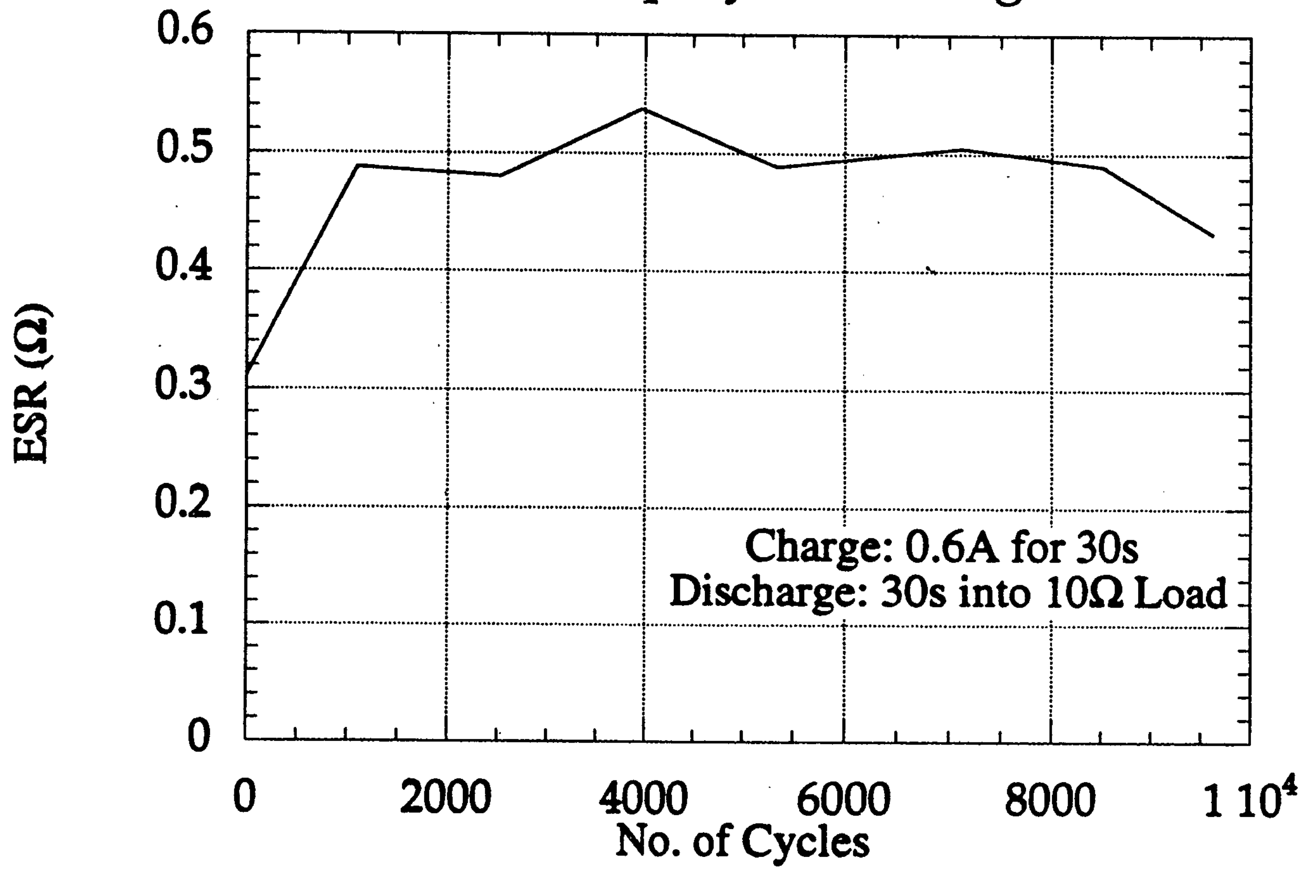
KTICap Cycle Testing

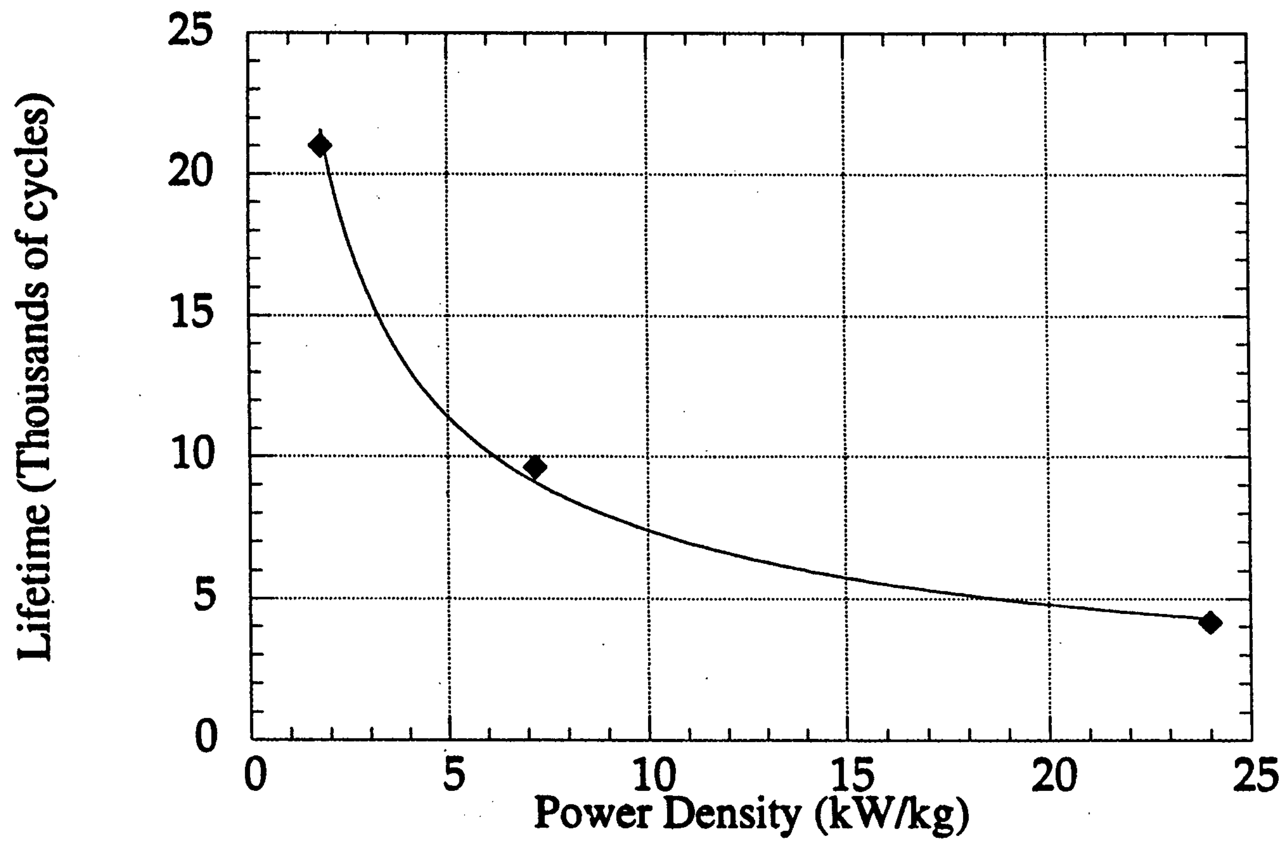


KTICap Cycle Testing

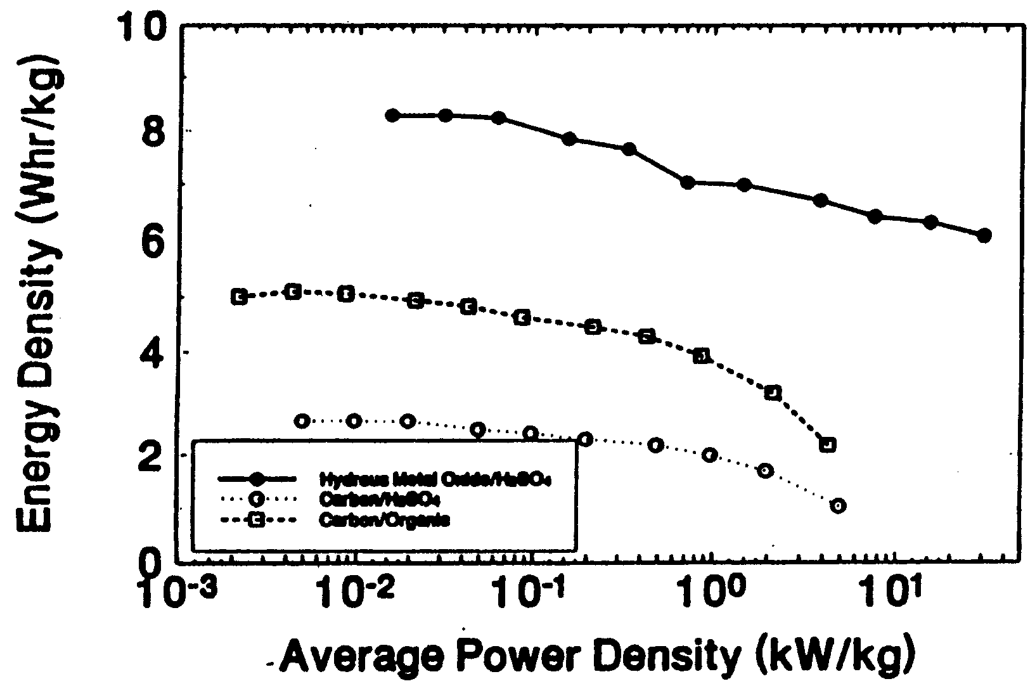


kti

Lifetime as Function of Power Density



Energy Density vs. Power Density for Electrochemical Capacitors Made with Different Materials



ARL Proprietary

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Summary of Capacitor Technology

Construction			Performance									Status	
Name	Electrode Configuration	Electrolyte	Energy (kJ/kg)	Density (kJ/l)	Resistance (Ω-cm^2)	Max. Power	Cost	Voltage	Typical Capacitance (F)	Largest Unit	Basis for Projection	NASA Readiness Level
NEC Supercap	bipolar carbon/carbon composite	sulfuric acid	4.7	6.8	.16	4 kW/kg	low	15	470	55 kJ	Manufacturer's spec sheet	6
NEC FY	bipolar carbon	sulfuric acid	1.2	1.98	45	—	low	5	2.2		Manufacturer's spec sheet	6
NEC FE	bipolar carbon	sulfuric acid	0.036	0.65	1.9	—	low	5	1.5		Manufacturer's spec sheet	6
Panasonic	spiral wound, single cell carbon	organic	7.9	10.4	7	2.7 kW/kg	low	3	470, 1500	6.7 kJ	Commercial device	6
Evans	prismatic carbon	sulfuric acid	0.72	1.8	1	—	low	11		40 kJ	Manufacturer's spec sheet	5
Seiko Instruments	polyacene polymer, button cell	organic	6.84	17.6	12	—	—	5	2.5		Manufacturer's spec sheet	6
Pinnacle Research Institute	bipolar pseudocap using mixed oxides (Ru,Ta)	sulfuric acid	18 46.8	50.4 144	$<10^{-2}$ $<10^{-2}$	2 kW/kg	high med	100	0.01	15 kJ	Manufacturer's testing Projections	5/6 —
Maxwell/ Auburn	bipolar carbon/metal composite	KOH organic	4.32 22	7.2 32.4	0.1 - 0.2 1.5	1.7kW/kg 3 kW/kg	med med	28 3	12 2700	6 kJ 12.5 kJ	Engineering prototypes	5/6
SAFT	bipolar carbon	organic	10.4	15.8	15	1.2kW/kg	low	3	175		Engineering prototype	5/6
ARL/Army KTI	Bipolar hydrous RuO_2	sulfuric acid	96 active mat'l only	187 active mat'l only	—	10 kW/kg	high	5	2.72	34 J	Lab cell	4
Livermore National Lab	bipolar aerogel carbon particulate	KOH	3.6	5.4	—	—	med	1	35		Lab cells	4
Sandia National Lab	bipolar synthetic, activated carbon	aqueous	5.0	6.1	0.35	1 kW/kg	med	1	3.5		Lab cells	4
Los Alamos National Lab	bipolar conducting polymer on carbon	solid organic	36-72	—	—	—	low				Projections	—
Technautics Hypercap	bipolar pseudocap, Ag-anode, C-cathode	solid $RbAg_4I_5$	1.98	12.6	ohms	—	—	0.6	—	—	Manufacturer's testing	6

Summary/Conclusions

* Electrochemical capacitors are high specific power and energy devices.
* Electrochemical capacitors are capable of hundreds of thousands of charge/discharge cycles.
* Electrochemical capacitors can be configured to meet the needs/requirements of human powered systems.

"COMPACT AND LIGHTWEIGHT ENERGY CONVERSION USING ELECTROSTRICTIVE POLYMERS"

Mr. Roy D. Kornbluh

SRI International
Menlo Park, CA 94025

Compact and Lightweight Energy Conversion using Electrostrictive Polymers

Presentation to

Prospector IX Human Power Systems Workshop

Roy Kornbluh

Ron Pelrine

SRI International

November 1997

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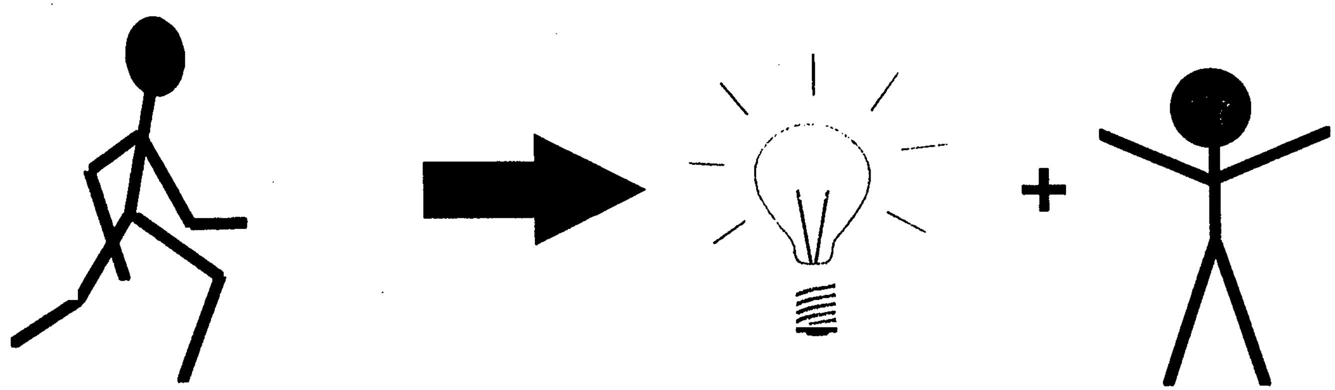
Problem Statement

- Develop a device that can efficiently convert human motion into useful amounts of electrical power with minimal mass, volume, and discomfort to the wearer.



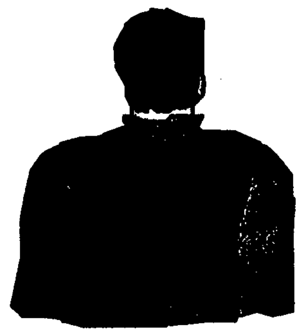
Technical Challenges

- Determine how human motion can be harvested without placing excessive burden on the wearer
- Develop an energy conversion technology that:
  - is efficient
  - has high energy density (to minimize volume)
  - has high specific energy (to minimize mass)
  - is impedance matched to human movement
    - large stroke
    - moderate forces
  - is rugged and reliable
  - can function over a range of environmental conditions
- Store and manage the generated power

Harvesting Human Movement

- Several possibilities that do not excessively burden the wearer

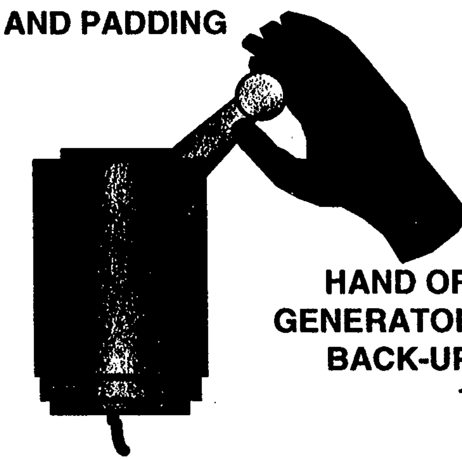
HEEL STRIKE AND SHOE FLEXURE
2 - 20W



BACKPACK SUSPENSION AND PADDING
0.5 - 5W

LIMB SWING
0.2-3W

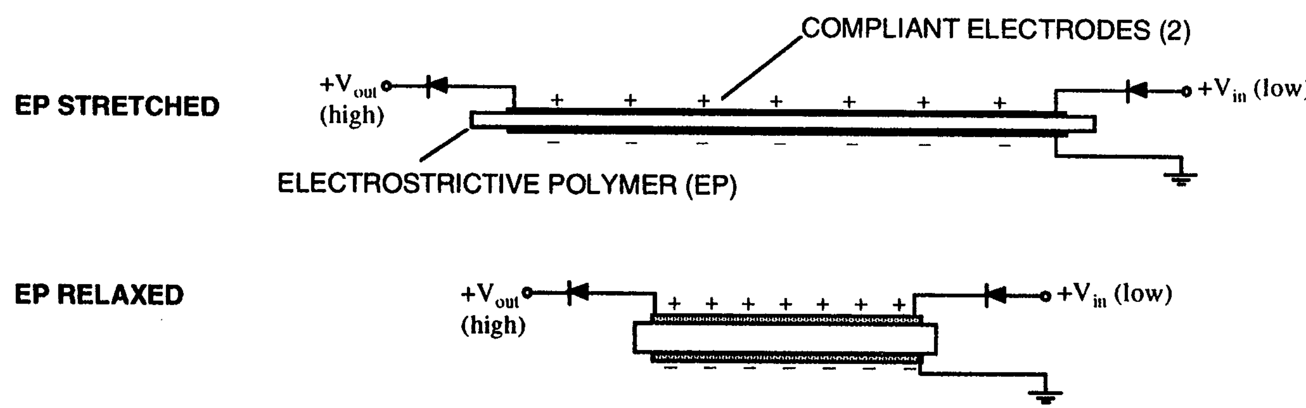
CHEST OR TORSO EXPANSION FROM
BREATHING OR ROUTINE MOVEMENT
0.1-1W



HAND OR LEG CRANKED
GENERATOR FOR EMERGENCY
BACK-UP (SHORT-TERM)
10-100W

Principal of Operation

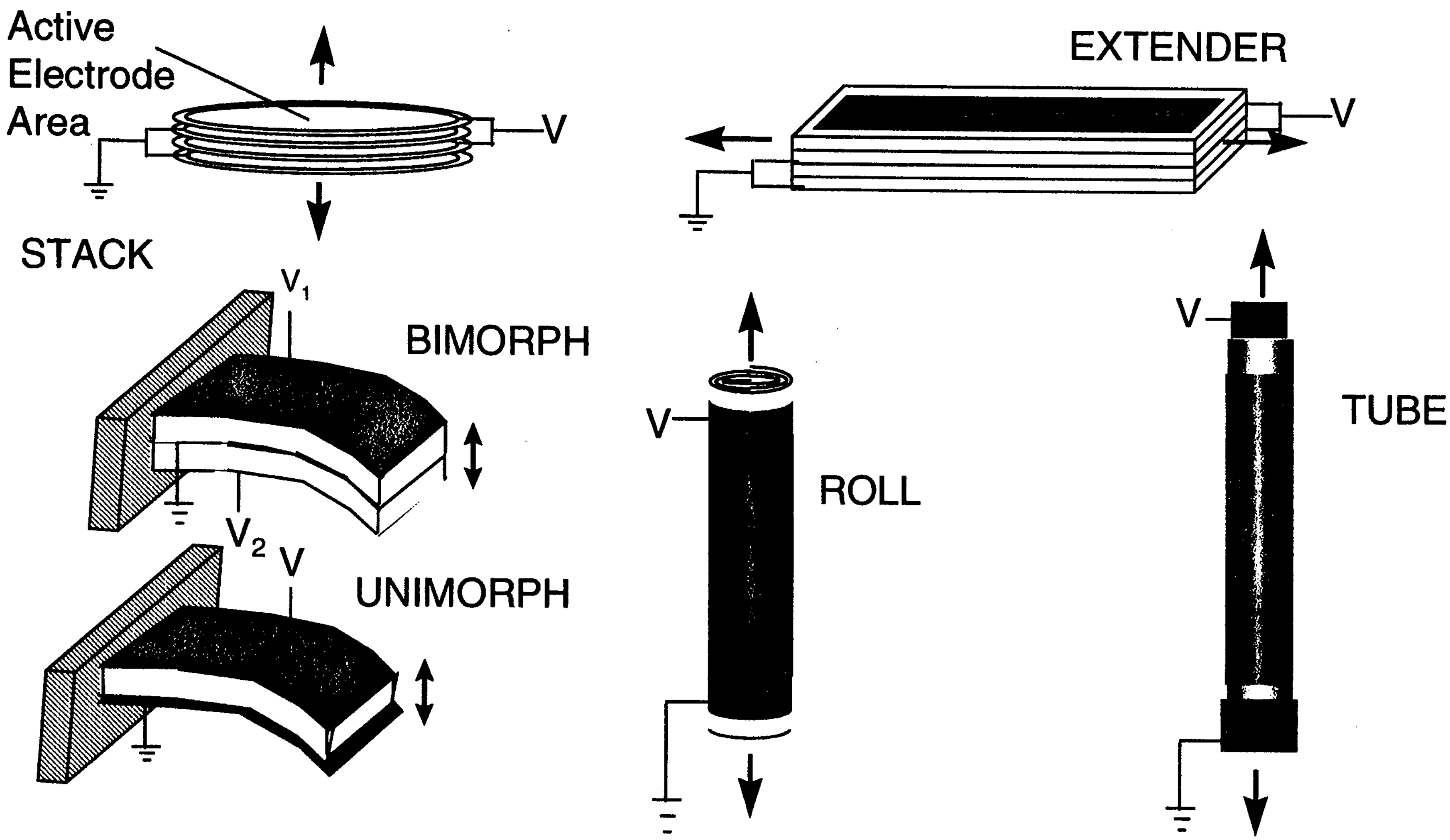
- Energy is generated due to a change in the capacitance as the film is stretched
  - $E = \frac{1}{2} Q_o^2 (1/C_f - 1/C_i)$
  - $C = \varepsilon_r \varepsilon_o$ x film area/film thickness
  - nearly incompressible polymers increase in area and decrease in thickness when stretched



Motivation for Electrostrictive Polymer Energy Conversion

- High energy output per stroke - volumetric and per unit mass
- High energy conversion efficiency - up to 90%
- Materials are soft - allow for large strains typical of human movement
- Flexible design options
  - direct drive - few moving parts, little wear
  - can be configured in almost any shape - easy to incorporate into clothing
  - performance is scale invariant - microscopic to macroscopic sizes
- Rapid response - DC to ultrasonic
- Rugged and reliable - already demonstrated >5 million cycles (and still counting) as an actuator
- Good environmental tolerance - silicone and polyurethane materials already in widespread usage in clothing and footwear
- low cost - inexpensive materials and simple manufacturing techniques
- Smart materials - transducer material can be incorporated into a structural or protective component and can also be used as capacitive or resistive strain sensor for personal monitoring

Possible Transducer Configurations



Transducer Technology Comparison

Transducer Type (Specific Example)	Max Strain (%)	Max Energy Density (J/cm^3)	Specific Density	Max Coupling efficiency k^2 (%)	Conversion Efficiency (%)
Electrostrictive Polymer Artificial Muscle					
(Silicone)	>100	0.7	1	90	90
(Polyurethane)	>50	1.1	1.1	40	80
Electrostatic devices (Integrated Force Array, MCNC)	>100	0.005	~0.7	>90	>90
Electromagnetic (voice coil*)	100	0.025	8	>90	>90
Piezoelectric					
Ceramic (PZT)	0.2	0.035	7.5	50	>90
Polymer (PVDF)	4	0.21	1.8	1.4	90

* Based on an array of 0.01 m thick voice coils, 50% conductor, 50% permanent magnet, 1 T magnetic field, resistivity of 2 ohm-cm, 40,000 W/m^2 power dissipation

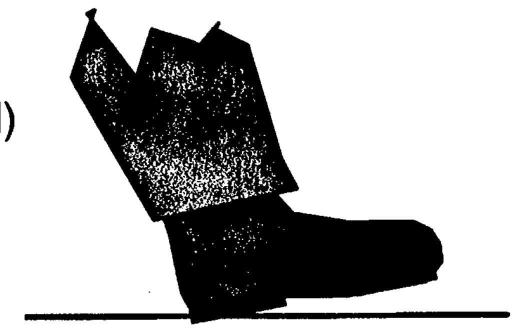
Measured Performance of Various Polymers as Actuators

POLYMER (Specific type)	Energy Density (J/cm^3)	Strain (%)	Pressure (MPa)	Young's Modulus (MPa)
POLYURETHANE Deerfield PT6100S	0.10	11	1.9	17
SILICONE Dow Corning Sylgard 182	0.034	32	0.21	0.7
FLUOROSILICONE Dow Corning 730	0.019	28	0.070	0.5
FLUOROELASTOMER Lauren L143HC	0.0080	8	0.20	2.5
POLYBUTADIENE Aldrich PBD	0.011	12	0.19	1.7
ISOPRENE Natural Rubber Latex	0.0052	11	0.094	0.85

- Even greater strains and energy density are possible with these elastomers operated as generators

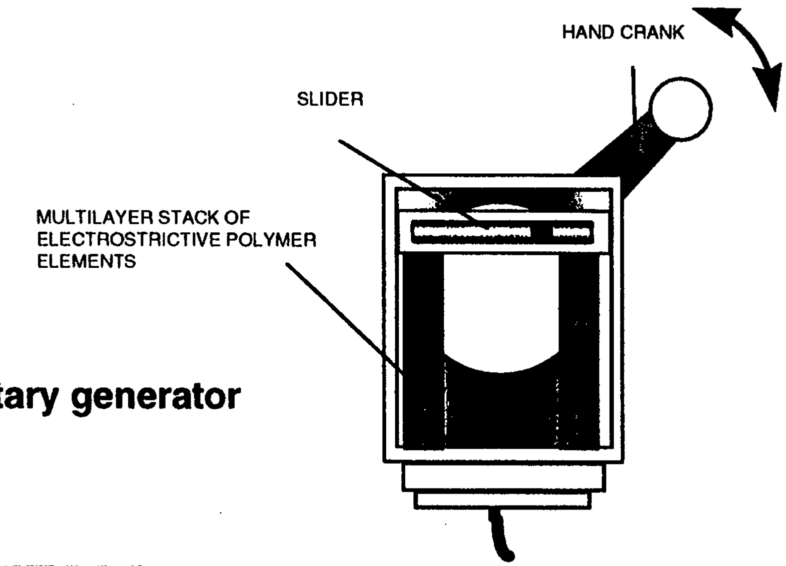
Specific Example: Heel-strike Generator

- Energy from the heel strike is "free" - it would otherwise be dissipated as heat
- Assume
  - the dynamic footfall force of a 70 kg person is 100 kg (~1000 N)
  - the force is decelerated through a distance of 1 cm
  - the energy conversion efficiency is 50%
  - two steps/sec (both feet)
- Energy converted per step is 0.5 x 1000N x 0.01 m = 5 J
- Power generated (both feet) is 10 W
- Assuming a conservative energy density of 0.2 J/cc, the amount of electrostrictive polymers needed to convert 10 J is about 50 g or 50 cc.
- Electromagnetic or piezoelectric devices would weigh more than 10 times this weight

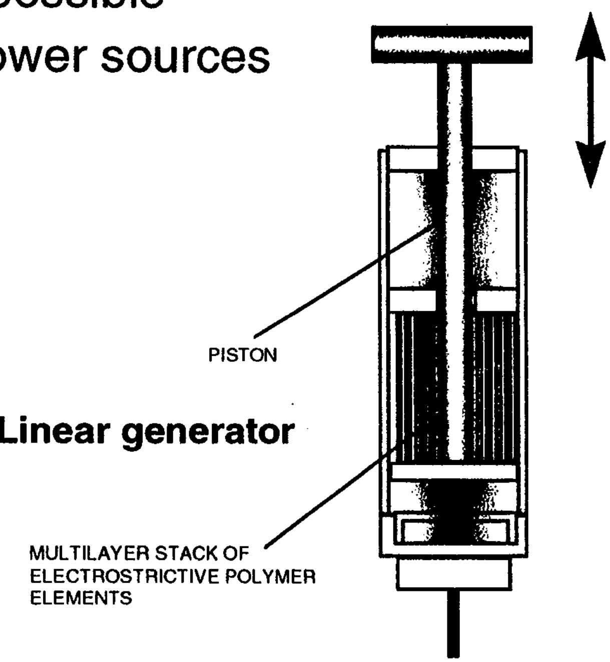


Human-powered Generators

- Large deformation capability of electrostrictive polymers allows for simple and efficient integration into generators
  - efficiency is not speed dependent
  - device can weigh 10x less than an electromagnetic generator with the same output rating
- Novel generator designs with few moving parts are possible
- Similar devices can also be couple to non-human power sources (e.g. engines, wind turbines)



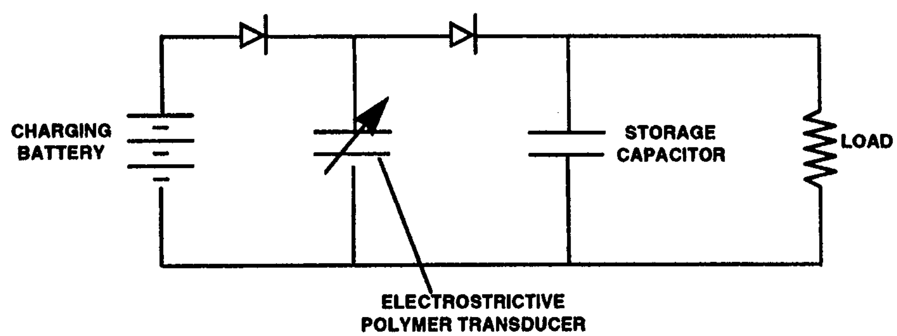
Rotary generator



Linear generator

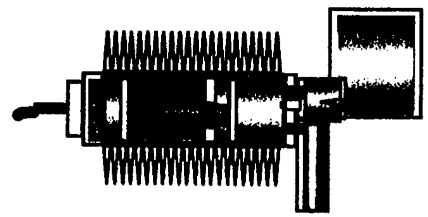
Power Storage and Management

- Voltage output will be high voltage time varying
- Short-term and long-term energy storage needed
  - short-term can be high-voltage capacitors
  - long-term will likely require voltage converters to standard batteries
- Circuitry should be "tuned" to the transducer for optimum efficiency
  - highly capacitive load
  - relatively low frequency operation

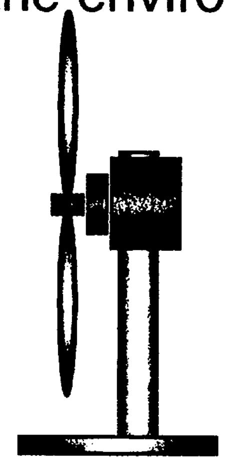


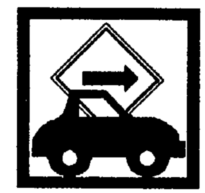
SIMPLE EMBODIMENT OF AN ELECTROSTRICTIVE POLYMER GENERATOR CIRCUIT

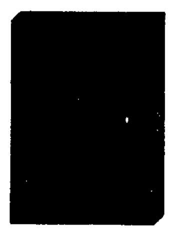
Related Power Generator Applications of Electrostrictive Polymers



- Combustion engines
- Energy scavenging or harvesting from the environment, e.g.:
  - waves
  - wind
  - passing vehicles or foot traffic
  - opening/closing doors







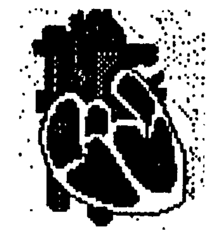
Conclusions and Directions for Research

- Electrostrictive Polymers have unique properties that make them well-suited for devices that convert human motion into electric power, e.g.:
  - high energy density
  - high efficiency
  - good impedance match - large strain capability with low to moderate forces
  - can be fabricated into a variety of configurations
- Electrostrictive polymers have already been used in actuators for a variety of applications
- Application of electrostrictive polymer technology to power generation requires
  - fabrication and testing of rugged and reliable transducer elements
  - design of devices to efficiently utilize human motion (e.g. heel-strike generator)
  - development of circuitry to efficiently utilize generated power

Electrostrictive Polymer Artificial Muscle Applications: Projects and Potential

DARPA project investigating electrostrictive polymers for sonar actuators

MITI (Japan) Micromachine Center project is investigating electrostrictive polymer artificial muscle for small robots for pipe inspection



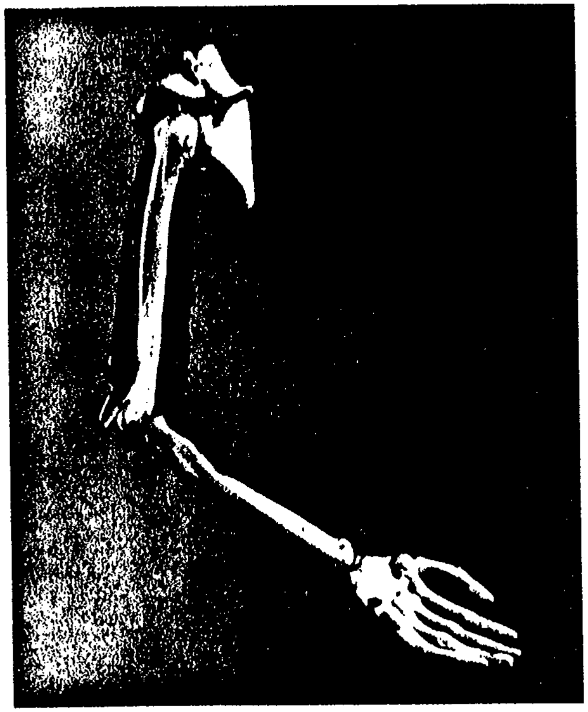
ONR sponsored development of improved actuators for robotics

DARPA sponsored development of a MEMS noise suppressor using an electrostrictive polymer loudspeaker

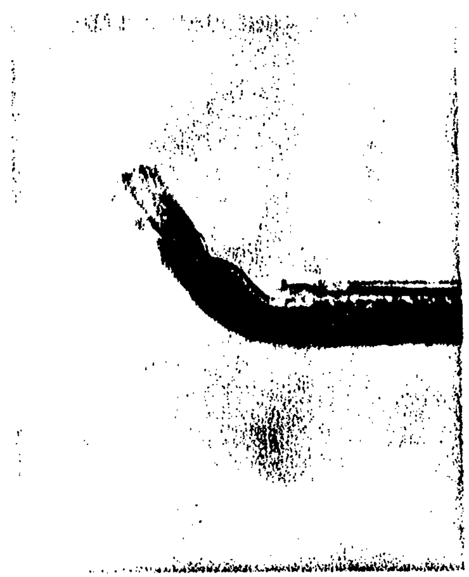
Many other applications and devices being investigated including:

- pumps and valves
- flapping wings and airflow control

Applications of Electrostrictive Polymer Artificial Muscle Actuators to Robots



ROLLED ACTUATORS ACT ANTAGONISTICALLY TO MOVE A SCALE MODEL OF A HUMAN ARM



BIMORPH ACTUATOR CAN FUNCTION AS AN INSECT-LIKE LEG OR WING

"LUNAR/MARS SPACE SUIT REQUIREMENTS"

Mr. Anthony P. Wagner

NASA Johnson Space Center
Houston, TX 77058

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Lunar / Martian Spacesuit Requirements

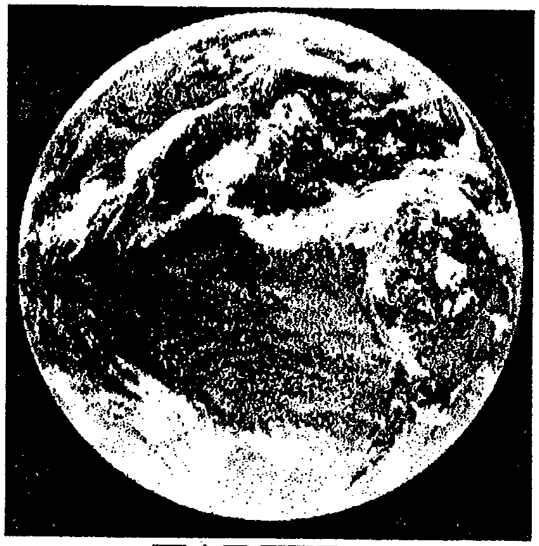
Anthony P. Wagner
NASA Johnson Space Center

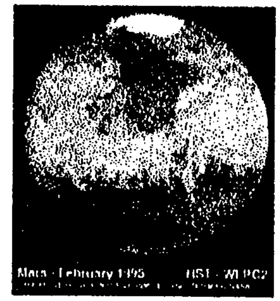
Status as of 11/3/97

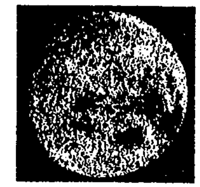
Mars EVA Design Reference Mission

- **Driven by Science Exploration**
  - Geology (most mobility demanding)
  - Core Sample Drilling
  - Instrumentation Set-up
- **Physical Infrastructure Interactions as needed beyond robot capability**
  - Construction
  - Repairs
  - ISRU Plant / Drill operation
- **Human Health**
  - Exercise
  - Mental Hygiene

EVA Advanced Research and Development Road Map



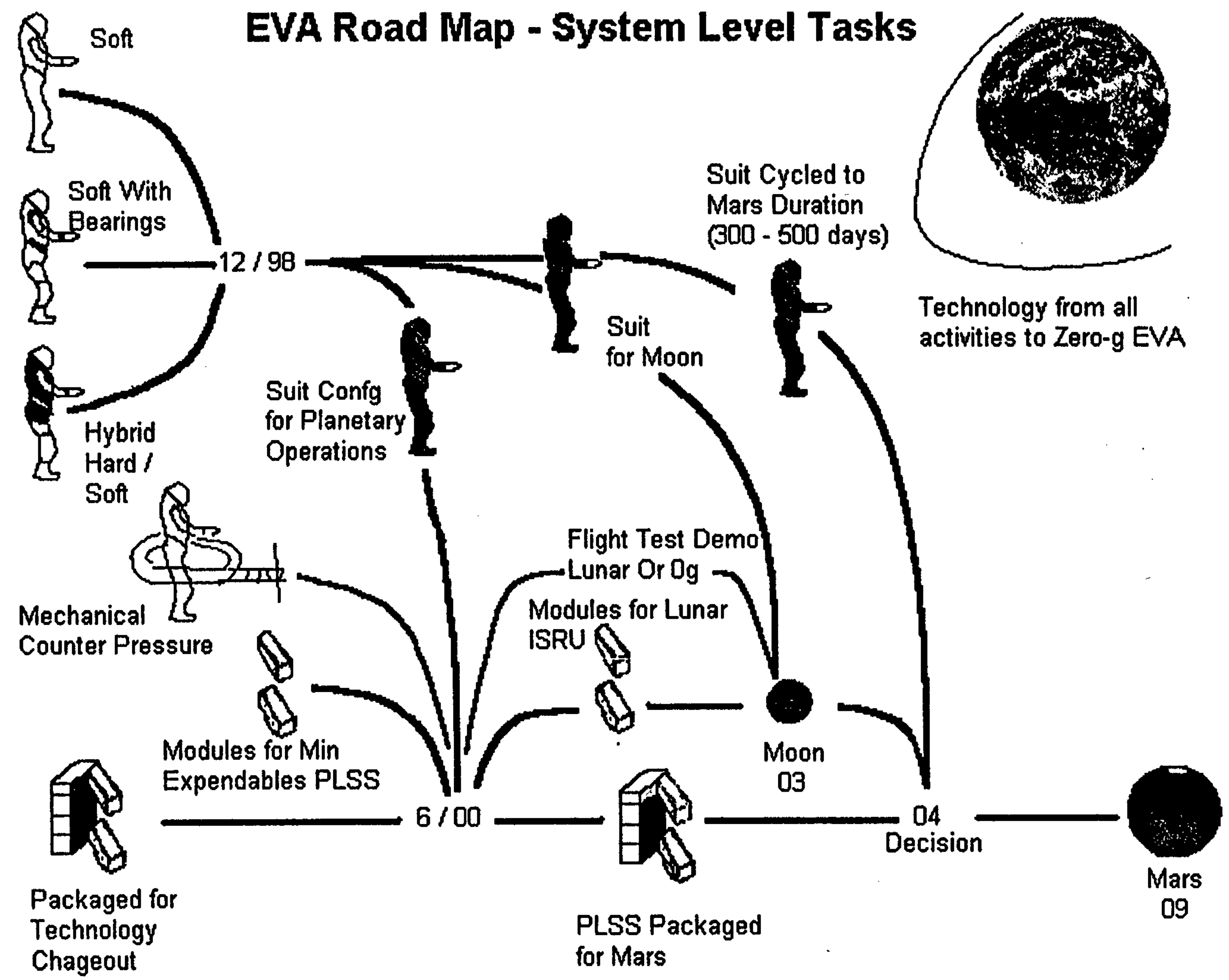




	EARTH	MARS	MOON
Gravity	1 g	0.379 g	0.167 g
Temperature	-50° C to 85°C with seasonal variation	-143° C to 17°C with seasonal variation	-178° C to 127°C
Atmospheric Pressure	O_2 / N_2 at 1.0 ATM.	CO_2 at 0.006 ATM.	Vacuum
Day Length	24 hr.	24.6 hr	672 hr (28 day)

Lunar / Martian Spacesuit Requirements	CREW AND THERMAL SYSTEMS DIVISION	
	Anthony P. Wagner	Nov. 3, 1997

EVA Road Map - System Level Tasks



Mars EVA Design Reference Mission

- **Operational Environment**
  - Six person crew with normal day consisting of two (2 person) teams EVA
  - 3 or 4 persons in rover for up to 10 days at a time
  - Light work and health EVA's by single persons are planned with biomed and location feedback constantly to base
  - Radiation storm protection provided by the Base or Pressurized Rover
  - Protection from large predictable storms (Macro Storms) provided by Base or Pressurized Rover
  - Protection from small unpredictable micro storms provided by suit

Lunar / Martian Spacesuit Requirements	CREW AND THERMAL SYSTEMS DIVISION	
	Anthony P. Wagner	Nov. 3, 1997

- **Space Suit System**
  - Design for Mars, Accommodate Moon, Technology Transfer for Zero g
  - Optimized for Surface Operations but Capable of
    - Zero g for transit contingencies
    - Mars Launch and Earth Entry Cabin Backup
  - Geology as Design Reference for Mobility
  - Reconfigurable Gloves (Mittens) to Meet Dexterity Needs
  - Removable, Cleanable Outer Garments for Dust / Thermal Protection
  - One Size Fits All Sizing with Minimum Overhead to Expand Commonality
  - Integral Emergency Backup System
  - Use the Natural Environment As Much As Possible
    - No Venting Constraints
    - Radiate / Convect for Heat Rejection

Lunar / Martian Spacesuit Requirements

Anthony P. Wagner

- **Space Suit System**
  - 3.7 psi Suit - No prebreathe impact
  - Flexible EVA time (4 or 8 hours) by modular expendables
  - Biomedical Instrumentation Communicated to Base and Self
  - Rich information available to EVA crewperson
    - Database from Base
    - Sensors (low light; binoculars; IR)
    - Continuous Navigation Aides
  - Rich Communications available between crew and to base
    - Voice & TV
  - First aid/evacuation provisions included "on back"
  - Allows "Overnight Camping" in Contingency Situations
  - Launch/Entry in EVA suit

Lunar / Martian Spacesuit Requirements	CREW AND THERMAL SYSTEMS DIVISION	
	Anthony P. Wagner	Nov. 3, 1997

- **Space Suit System**
  - Lightweight
    - PLSS < 40 Kg (85 lbm)
    - Suit < 30 Kg (60 lbm)
  - Low Volume
    - 8-hour PLSS volume 70% of STS EMU PLSS
  - Robust
    - Allow Fall on Sharp Rocks Without Danger Induced By Suit
    - Operation Unaffected by Dust and Dirt
  - Suit Comfortable Enough for Contingency Camp Out
    - Sleeping
    - Eating
    - Liquid and solid waste collection
  - Display and Controls to
    - Biomedical Display to Crewperson in Suit
    - Automatic Thermal Control with Manual Set Point Adjust
    - Integrated IR & UV visual view reproduction for day/night

Lunar / Martian Spacesuit Requirements	CREW AND THERMAL SYSTEMS DIVISION	
	Anthony P. Wagner	Nov. 3, 1997

- **Space Suit System**
  - PLSS with
    - $PPCO_2$ less than or equal to Mars atmosphere
      - 6mmHg (Mars Atmosphere) for nominal exercise
      - 10 mmHg for exercise peak
    - Thermal control w/o launch mass expendables
    - Humidity - Never saturated, no fogging, sufficient to prevent sparking
    - Sensor & Communications Minimum Volume and Integrated
      - Voice recognition > 98% with < 1% missed recognition
    - Communications - Suit Range at the Mars Horizon
    - Minimize Loss of Hydrogen Resource

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Goal is to eliminate majority or all of the mass, volume, and power of cooling loop by using an alternative such as thermoelectrics :

- Carnot maximum efficiency of cooling loop =(90F - -300F)/90F = 71 %
  (90F = skin temperature, -300F = Cryogenic oxygen temperature)

- Minimum metabolic rate = 400 BTU/hr = 117 Watts

- Maximum metabolic rate = 2000 BTU/hr = 585 Watts

- Efficiency of thermoelectrics and heat pipe determine output
  (Heat pipe needed to draw heat outside of 100% oxygen environment)

- Could also use substantial spacesuit boot surface for piezoelectric power
  (1/3 g will reduce output power capability)

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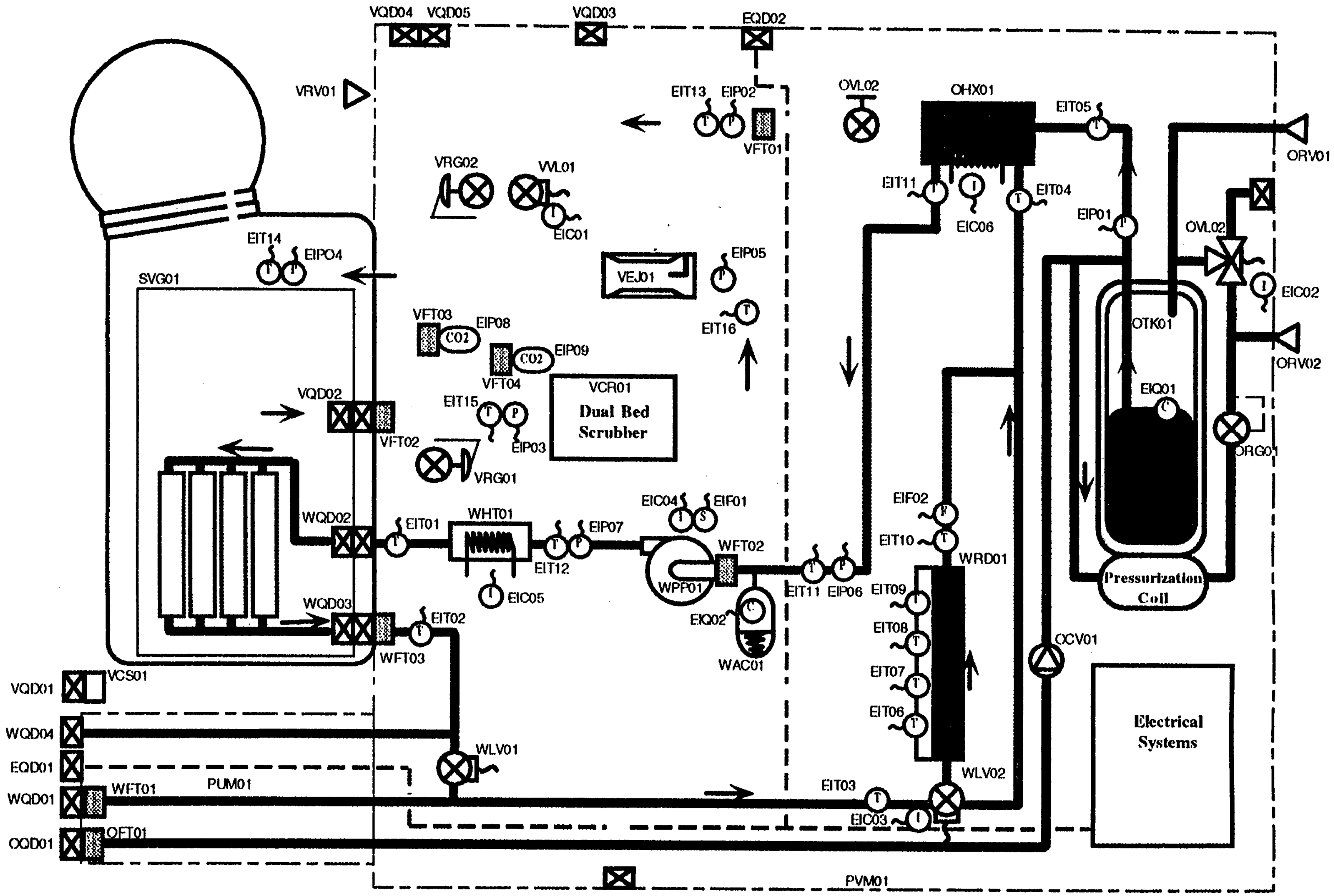
Savings through potential elimination of cooling loop :

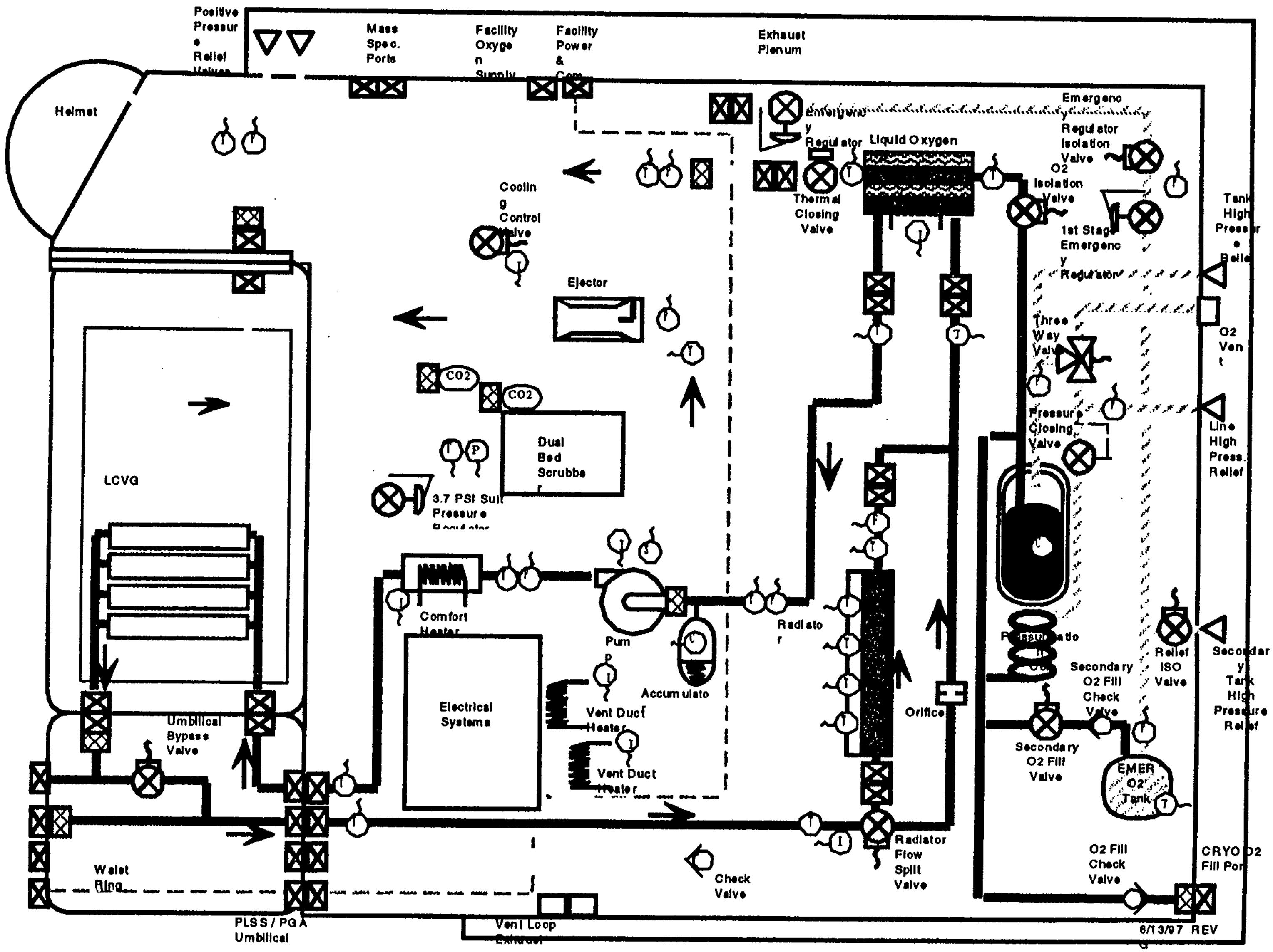
- No need for LCVG, comfort heater, pump, accumulator, radiator, plumbing, solenoids, 21sensors (T, P, I, C, S), water, filters, QD's
- Reduce mass 18 Kg (38 lbm) out of 68 Kg (145 lbm) - goal is 40Kg (85 lbm)
- Reduce volume by 19 %
- Reduce power demand 25 out of62 Watts - plus generate power during cooling phase if replaced with thermoelectrics

ADVANCED SUIT PROJECT: PLSS ITEM LIST



2/5/97 REV B

ADVANCED SUIT PROJECT CPLSS



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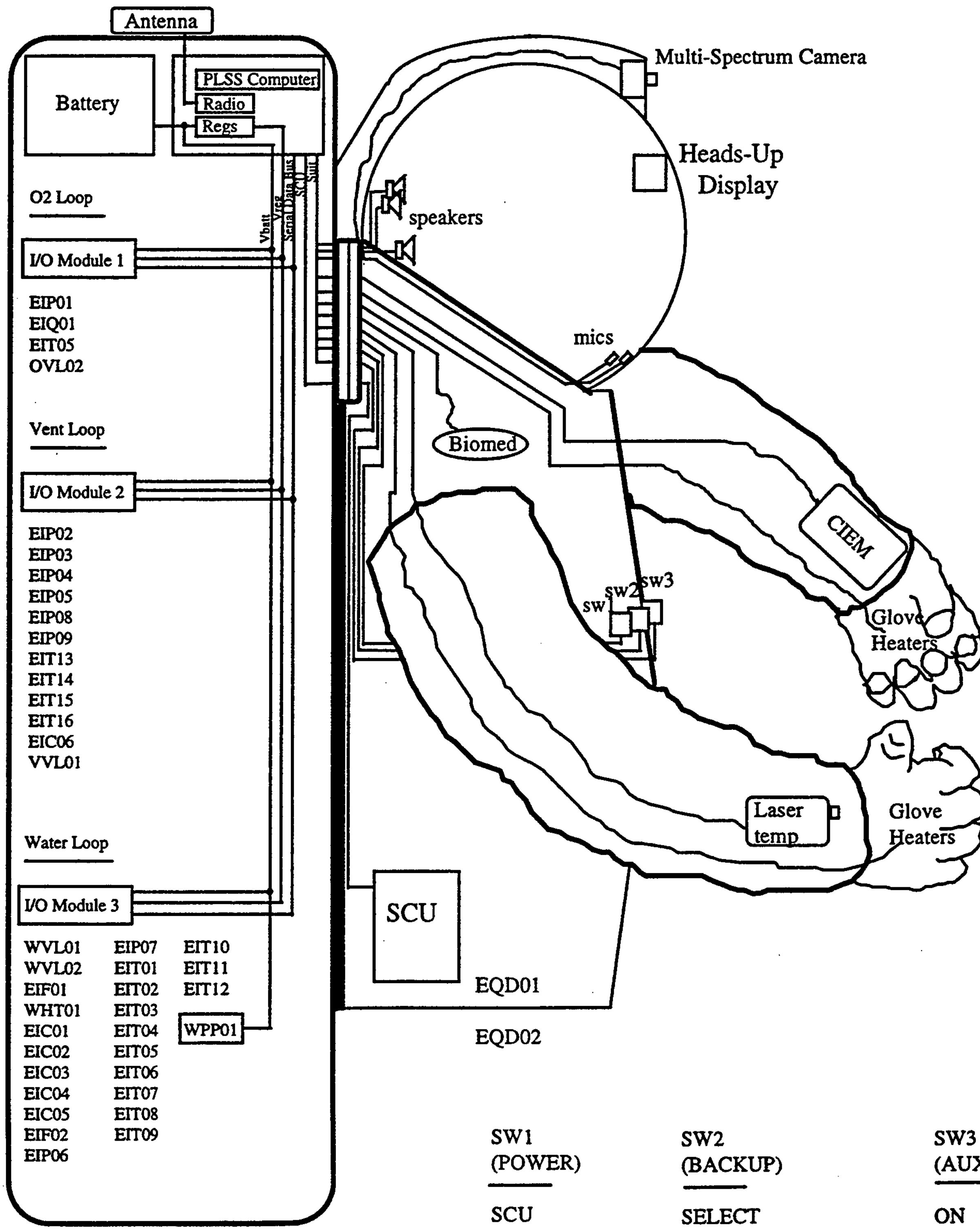
Advanced Spacesuit Electrical Schematic



SW1 (POWER)	SW2 (BACKUP)	SW3 (AUX PWR)
SCU	SELECT	ON
	OFF	
BATT	ACKNOWLEDGE	OFF

Tony Wagner 3/12/97

TECHNOLOGY SESSION 2

"INTEGRATED POWER MANAGEMENT FOR MICROSYSTEMS"

Mr. Dwayne N. Fry

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6009

Integrated Power Management for Microsystems

Presented at the Prospector IX Workshop
November 3-5, 1997

Dwayne N. Fry
Alan L. Wintenberg
Bill L. Bryan

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There is a need for a universal power module for microsystems. This module should provide power conditioning, energy storage, and load matching for a variety of energy sources and loads such as microelectromechanical systems (MEMS) and wireless sensors and micro-robots. There are a variety of potential ambient and human powered energy sources, which can supply some of the power needs of the military. The challenge is to capture these available sources of electrical energy and condition them to meet the voltage, current, and overall power demands of field-deployable microelectronics and MEMS-based devices such as wireless sensors and micro-robots. Most natural and man-made energy sources found in the environment have a low specific power and are not generally available on a continuous basis. Likewise, human-based energy sources must be optimally managed to meet the power needs in the field. Therefore, a power supply must have the ability to capture the available energy and store it in such a manner to be useful to meet the mission requirements of the device that is connected to the source. It must continuously monitor the status of energy stored and determine the expected demands of the device. A microelectronics-based power management chip can be developed to meet these objectives.

The major challenge in realizing this concept will be the design of an intelligent power-conditioning chip that consumes a minimum of power to perform the functions of power conditioning, storage, load matching, and status monitoring.

For a versatile chip design that can use a variety of energy sources, it is important to not constrain the energy source characteristics unduly. One suggested approach assumes only that the source is capable of delivering charge to a small capacitive load. This would be true for photovoltaic, piezoelectric, rotary or linear electric generators, thermoelectric and many other sources. As shown in Fig. 1, the resulting source voltages are monitored, and when a sufficient value is present, the power converter will multiply the voltage up to the storage supply voltage

and transfer it to storage. The storage element may be an ultracapacitor or rechargeable battery. Power would be delivered to the load through another switched capacitor circuit. This would allow metering of the power delivered to the load and, if needed, a voltage transformation. The metering function could also be used to help keep track of the amount of energy remaining in the storage element. A reserve energy storage element would be used to maintain power for the intelligent power controller, which is responsible for administering power transfers and for monitoring the demand signal from the load. It is anticipated that the load may require some very low level of power continuously (for a wake-up circuit, for preventing loss of memory, etc.), so an unswitched low-power output is provided. When the demand signal from the load signals a request for significant power, the intelligent power controller replies using the power status signal. If sufficient power is available in the storage element, then the power status signal is true and power is transferred to the load until the demand ceases. Another function of the intelligent power controller is to recharge the reserve energy storage element periodically.

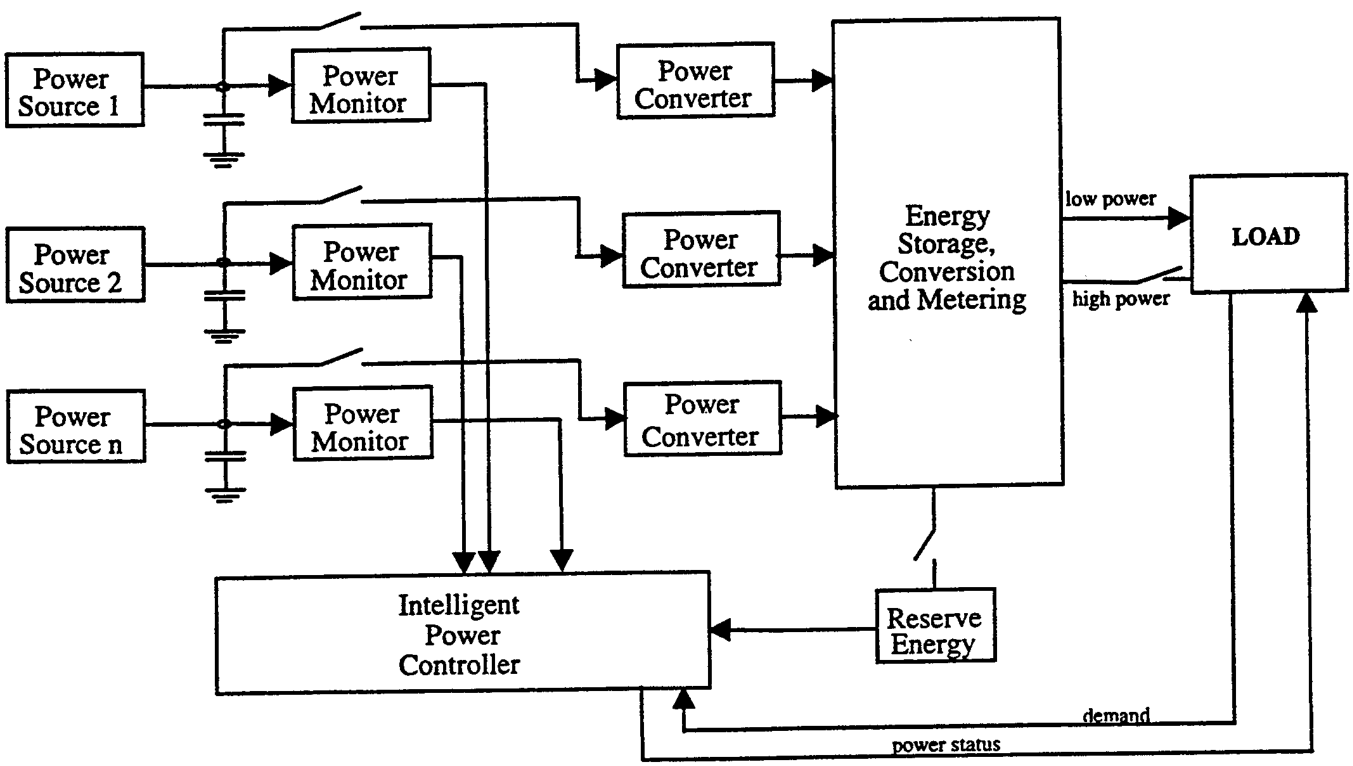

Fig. 1. Concept of power conditioning chip

The power conditioning integrated circuit (IC) would be implemented using CMOS technology. Integrated circuits fabricated using standard CMOS processes offer a number of features well suited to this application: digital circuits that require essentially no static power, low-power analog circuits, and good switches that are necessary for switched capacitor circuits. It should be possible to implement the entire circuit using a single IC with a very limited number of external components (such as capacitors too large to implement on the IC, i.e., those greater than a few tens of pF.) A prototype device would be made using a 1.2 or 0.8 micron process that would allow 5-V operation. This choice should not be restrictive as the same circuit could be converted to other CMOS processes. Processes of 0.5 micron or smaller would allow a greater density of logic for a given die size, but would be limited to 3.3-V operation. To deliver greater voltages to the load, a 3-micron process could be used which would allow approximately 20-V operation, or external components could be added to implement a boost dc-dc converter.

The prototype power conditioning IC would be capable of delivering a peak power of 100 mW at 5 V. The nominal operating condition would be a very low duty cycle for a relatively high power load, and a low-power source available for long periods of time, or a moderate-power source available intermittently. An example would be a wireless sensor and transmitter requiring 100 mW for 10 ms every 10 minutes and a source delivering perhaps five microwatts continuously. However, the device should also be capable of delivering approximately 100 mW continuously if sufficient power is available from the sources. Scaling for higher power outputs would be addressed by including features that would allow using multiple devices in parallel, or by resizing power sections of the IC to allow greater power input and output levels.

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Integrated Power Management for Microsystems

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Presented at the Prospector IX Workshop
November 3-5, 1997

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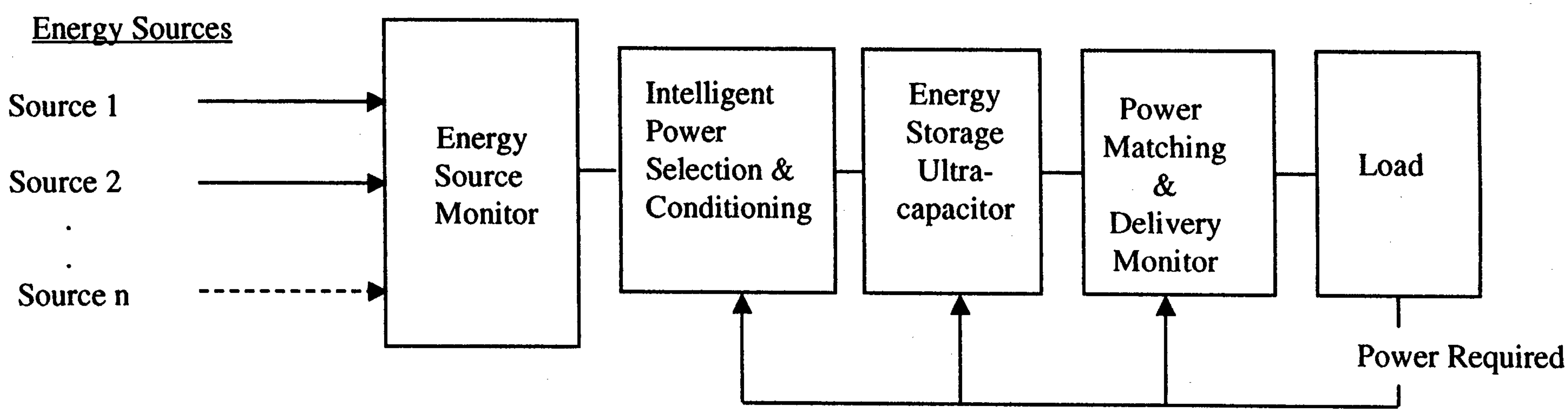
Universal Power Module Will Condition a Variety of Energy Sources and Match to a Variety of Loads

- Most energy sources do not naturally produce suitable power for the load, i.e.. proper voltage level
- Most human powered energy sources are intermittent and have a low specific power
- A number of loads such as wireless sensors and transmitters require power on an intermittent basis
- Intelligent power module will capture energy, store, condition the energy to proper voltage, and deliver to load on demand

Concept of An Integrated Intelligent Micropower Supply



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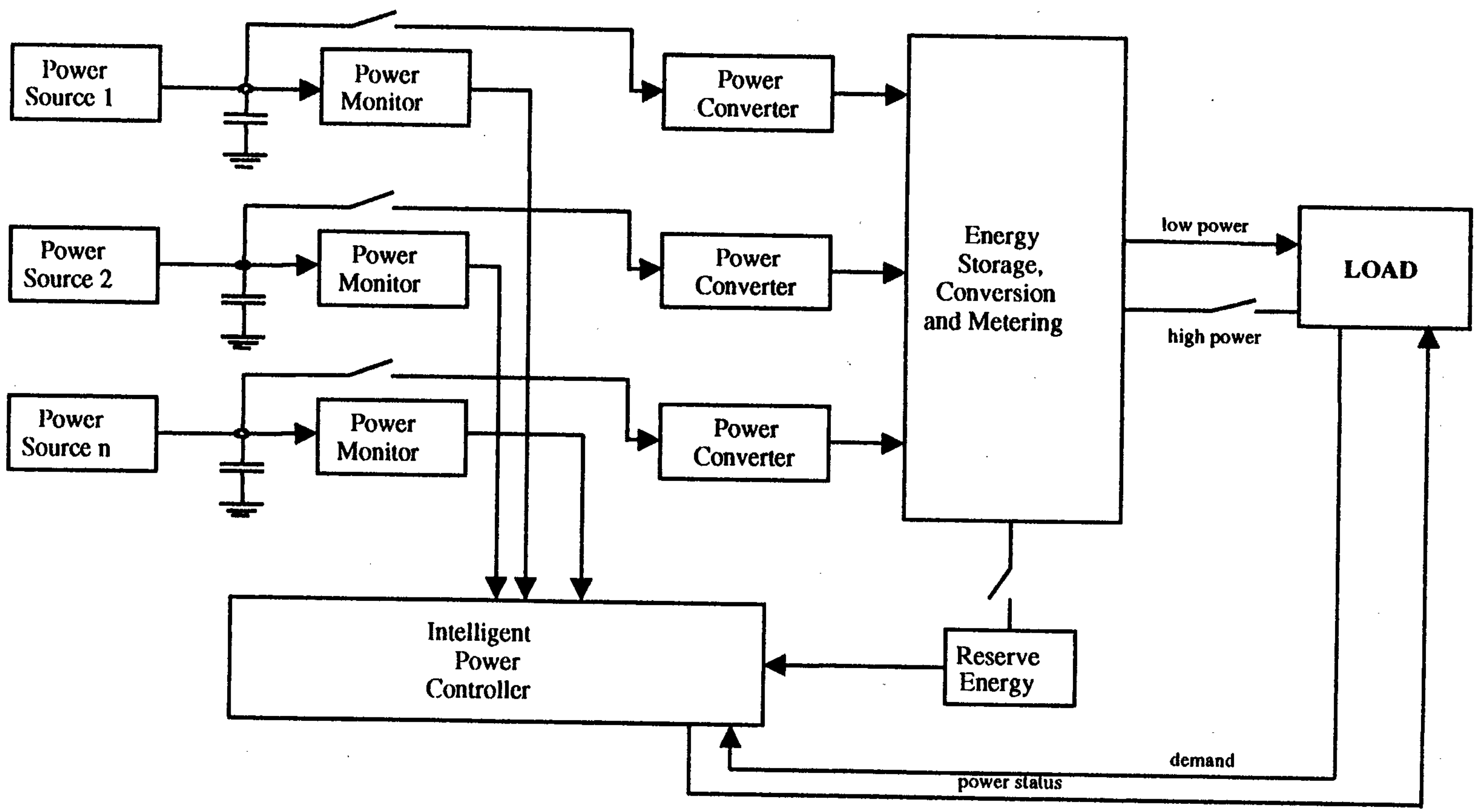
Concept of Power Conditioning Chip



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The Universal Module Performs Several Functions

- Power monitor determines status of charge collected from energy source
- Power converter converts charge to voltage for storage
- Storage medium also matches to load requirements and keeps track of available stored energy
- Intelligent controller administers power transfer to load and monitors demand signal from load
- Reserve energy supplies power to intelligent controller

The Power Module Could be Implemented on a Chip Using CMOS Technology

- CMOS digital logic circuit requires essentially no static power
- Capability of low-power analog circuits
- Provides good switches
- Five volt operation possible with 1.2 or 0.8 micron process
- Twenty volts with 3 micron process
- Peak power delivery approximately 100mW at 5 V
- The concept should be scaleable depending on load power requirements

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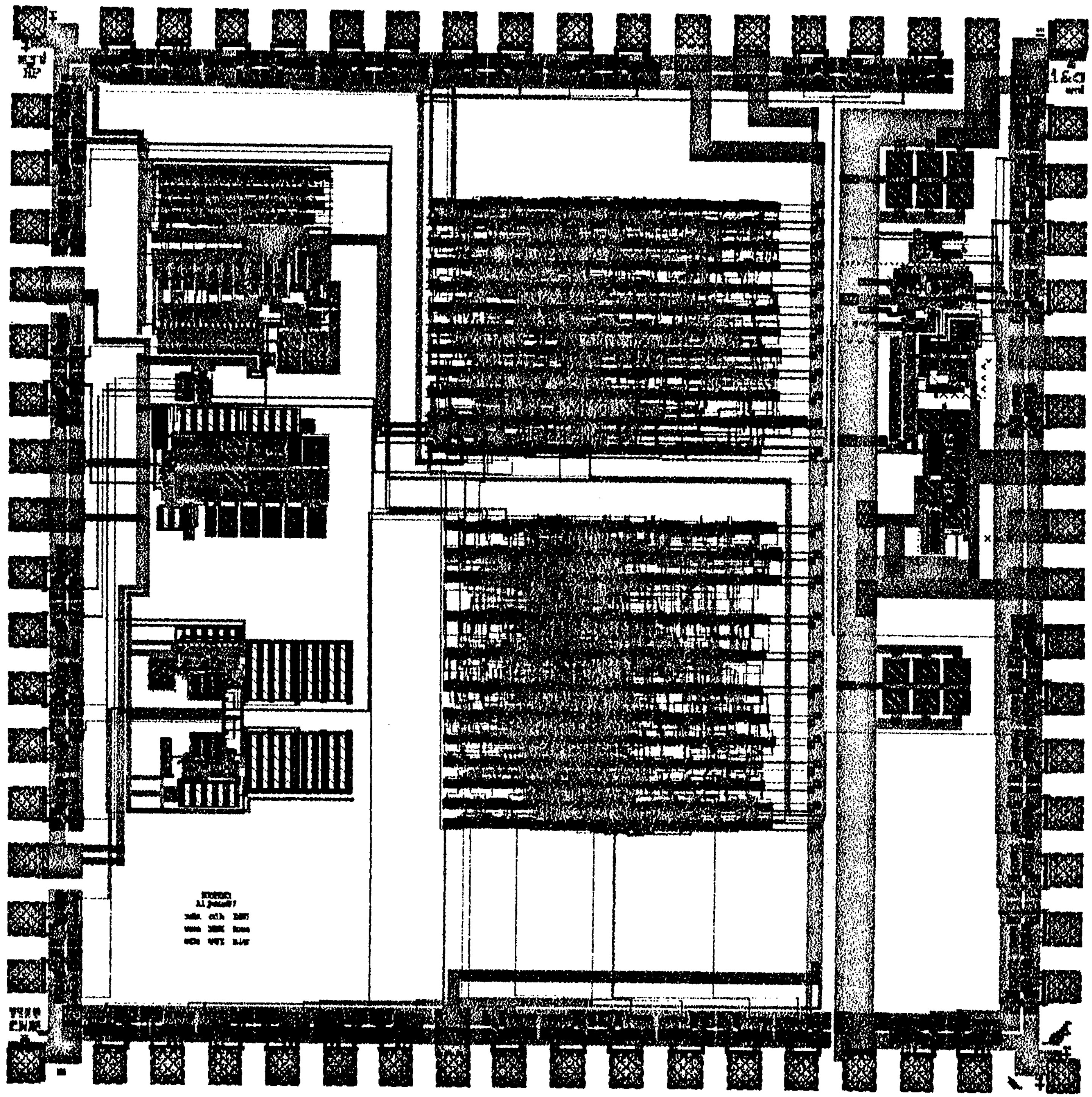
Our First Fully Integrated Wireless Data-Acquisition Chip

- Two Thermometers
- Two Uncommitted Inputs
- 10-bit ADC
- Control Logic
- Spread-spectrum Radio-frequency Transmitter



"SEIKO HUMAN POWERED QUARTZ WATCH"

OVERVIEW

Mr. Masakatsu Saka

Epson Research and Develpment Inc.
San Jose, CA 95134

DETAILS OF THE DEVICE

Mr. Kinya Matsuzawa

Seiko Epson Corporation
Nagano-ken, 392 Japan

APPLICATIONS OF AGS

Mr. Kinya Matsuzawa

Seiko Epson Corporation
Nagano-ken, 392 Japan

Kinetic Generator System

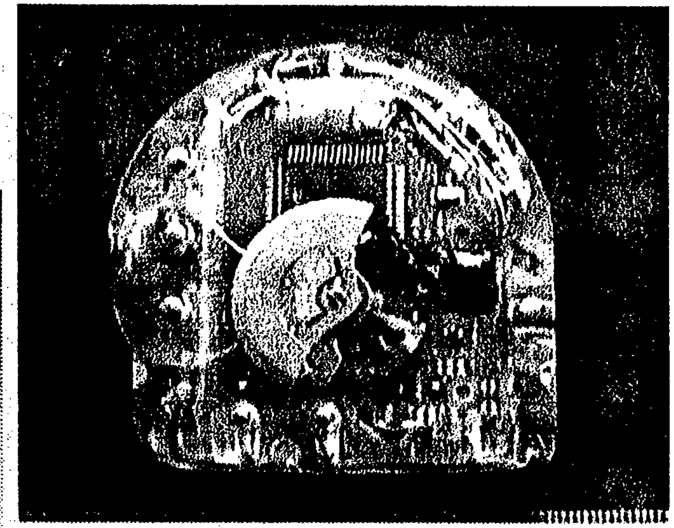
Epson Research & Development Inc.

Masakatsu Saka

Seiko-Epson Corp.

Kinya Matsuzawa

Auto generating system



KINETIC

SEIKO EPSON CORPORATION

Seiko's Automatic Generating System (AGS)

- Background of Seiko watch
- Concept of Automatic Generating System
- Details of mechanical feature
- Details of electrical curicuitry
- Further application of AGS

Background of Seiko watch

- 1969 The first quartz watch in the world
- 1972 Mass production of quartz watch
- 1974 The first liquid crystal digital watch in the world
- 1981 The first liquid crystal TV in the world (watch type)
- 1985 The first liquid crystal color TV in the world (palm top type)
- 1988 The first kinetic energy watch in the world (AGS)

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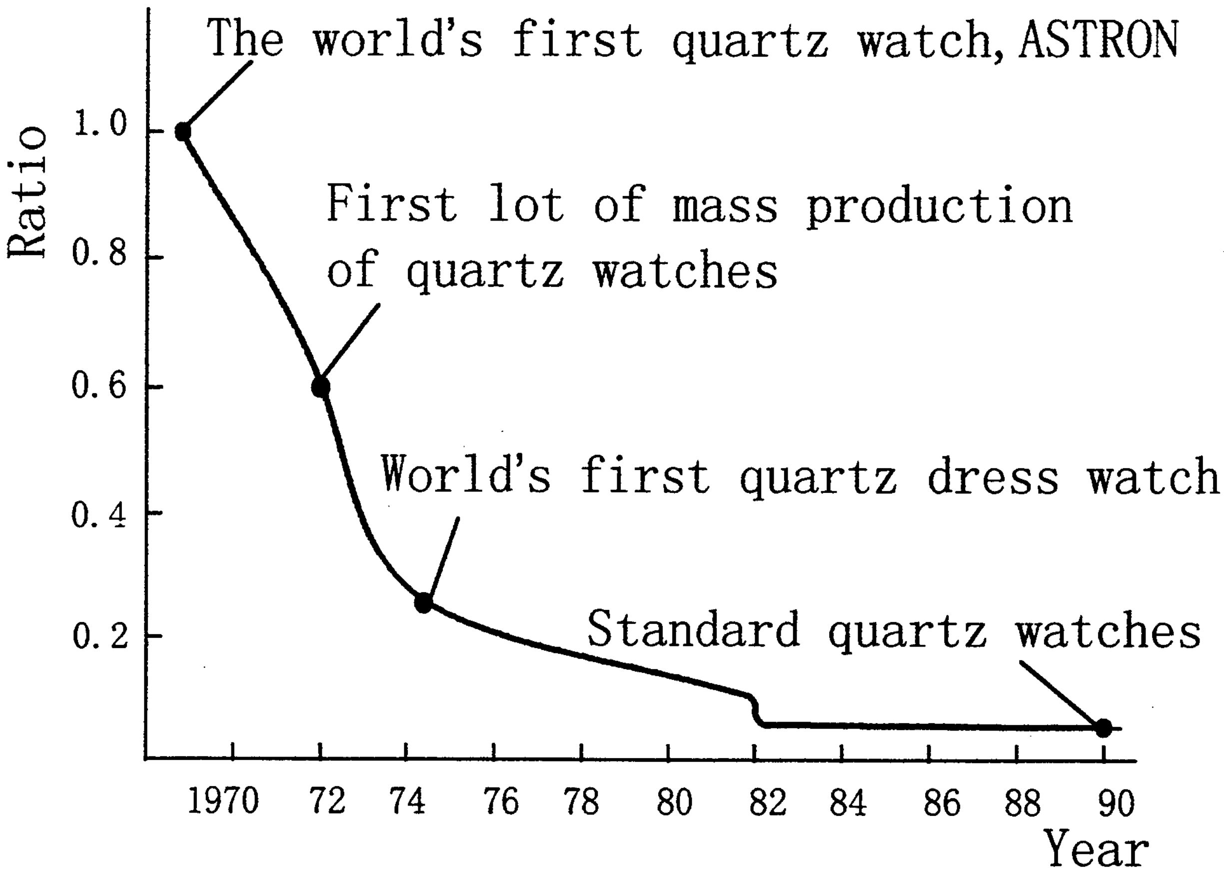
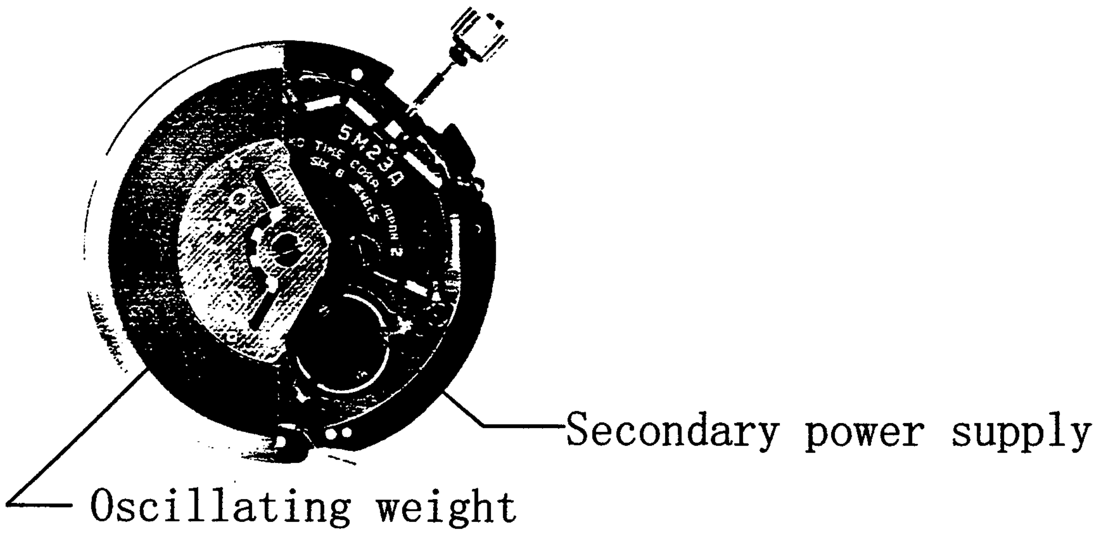
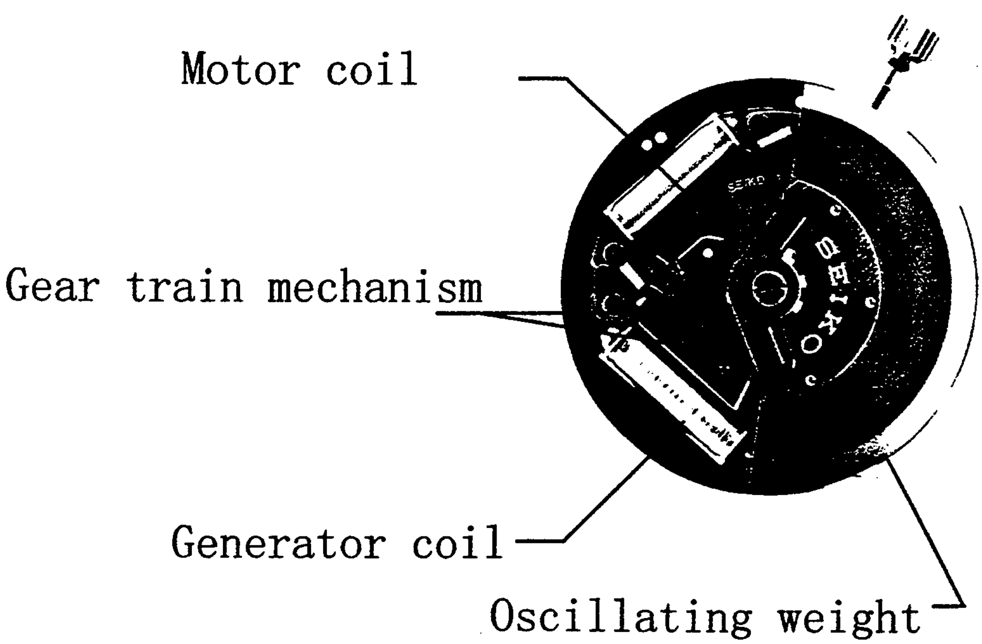


Trend in electrical current consumption (Seiko Epson data)

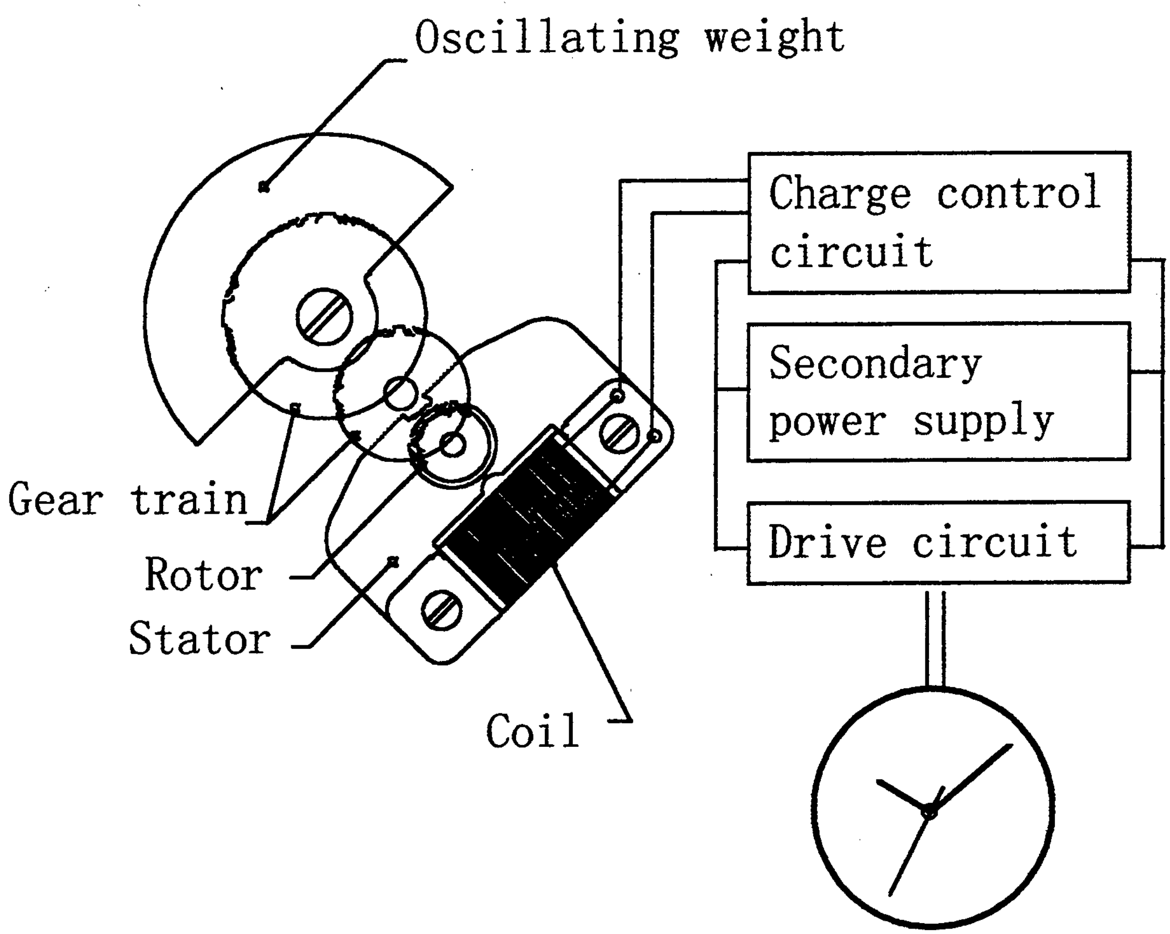
Concept of AGS

- Rotating an oscillating weight through moving an arm
- Accelerating rotation by gear train and transferred to a magnetic rotor
- Generating induced voltage in a coil by high speed rotation of a rotor through a stator
- Rectifying induced current and Storing it in a source





AGS appearance



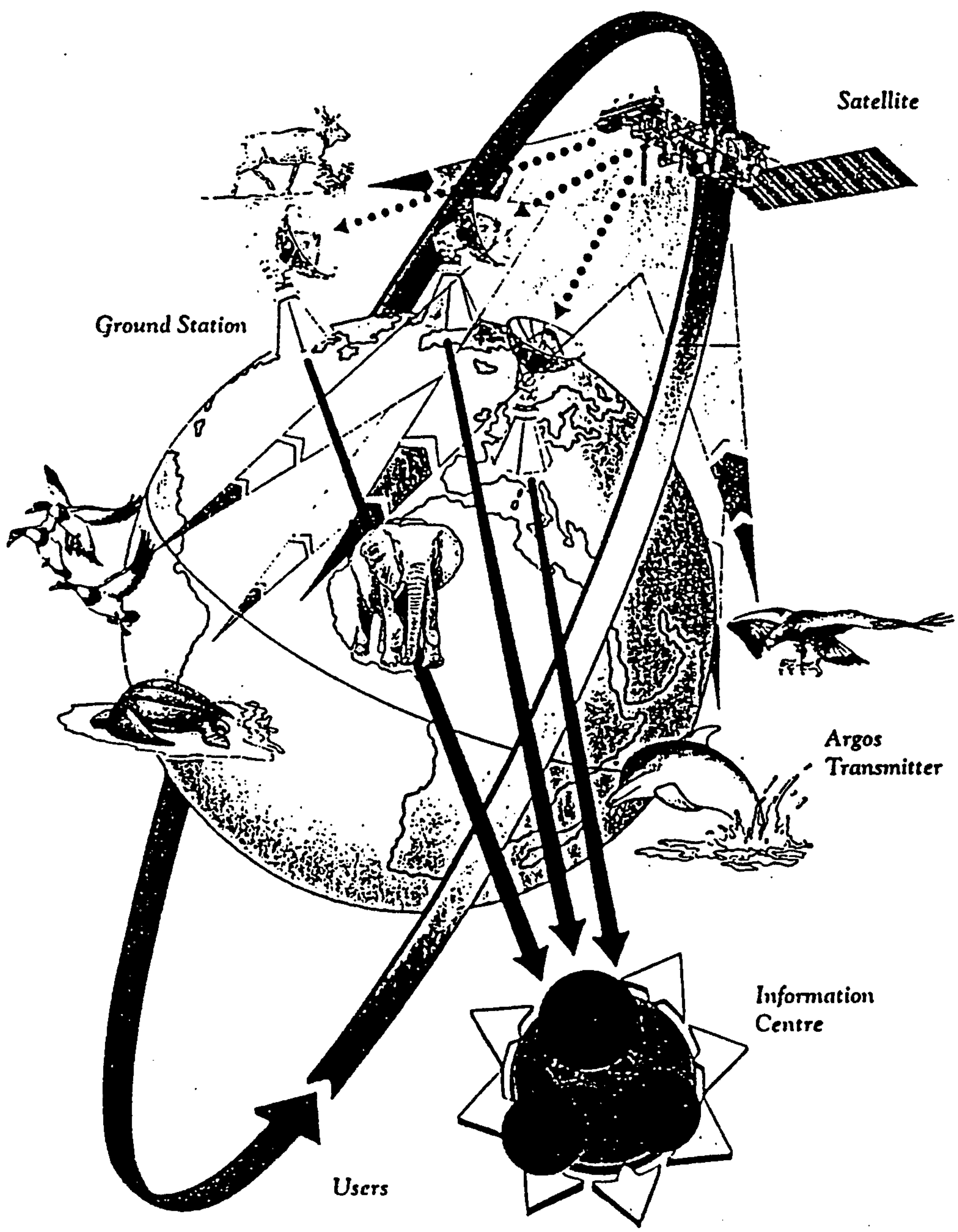
AGS outline diagram

The feature of Seiko's AGS

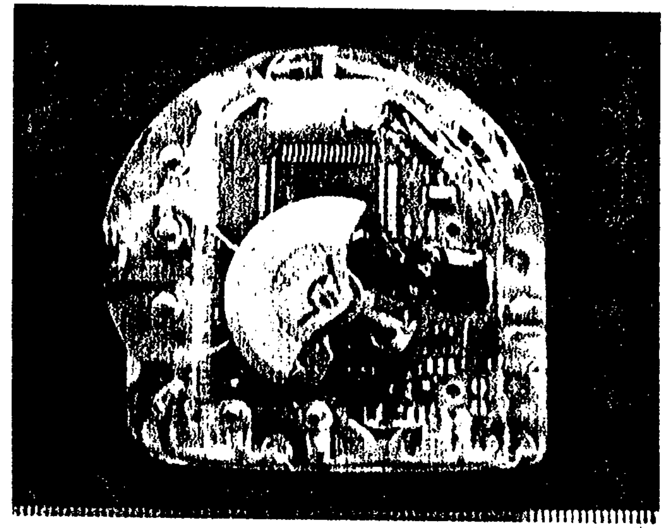
- Consistency and stability of generation power from random movement of an oscillating weight (Frequent change of very slow motion and high speed motion)
- Very slow motion-100 times accelerated rotation through gear trains
  - High speed motion-Shock absorption mechanism
- Constant power supply even if induced voltage lowered
  - a second power supply circuitry for raising induced voltage

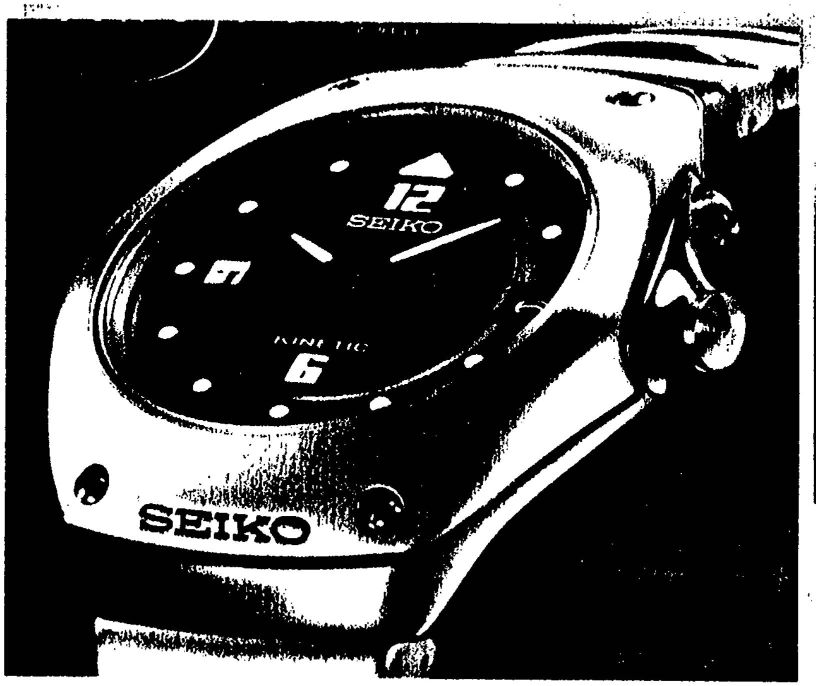
Further application of AGS

- Ecological research
  - A transmitter for tracking behavior of migratory animals (a whale,a dolphin, a migratory bird) and sending data of them to a station via satellite.
  - Need of constant power generation for a transmitter during long time(1-2yrs)


Satellite
Ground Station
Argos
Transmitter
Information
Centre
Users

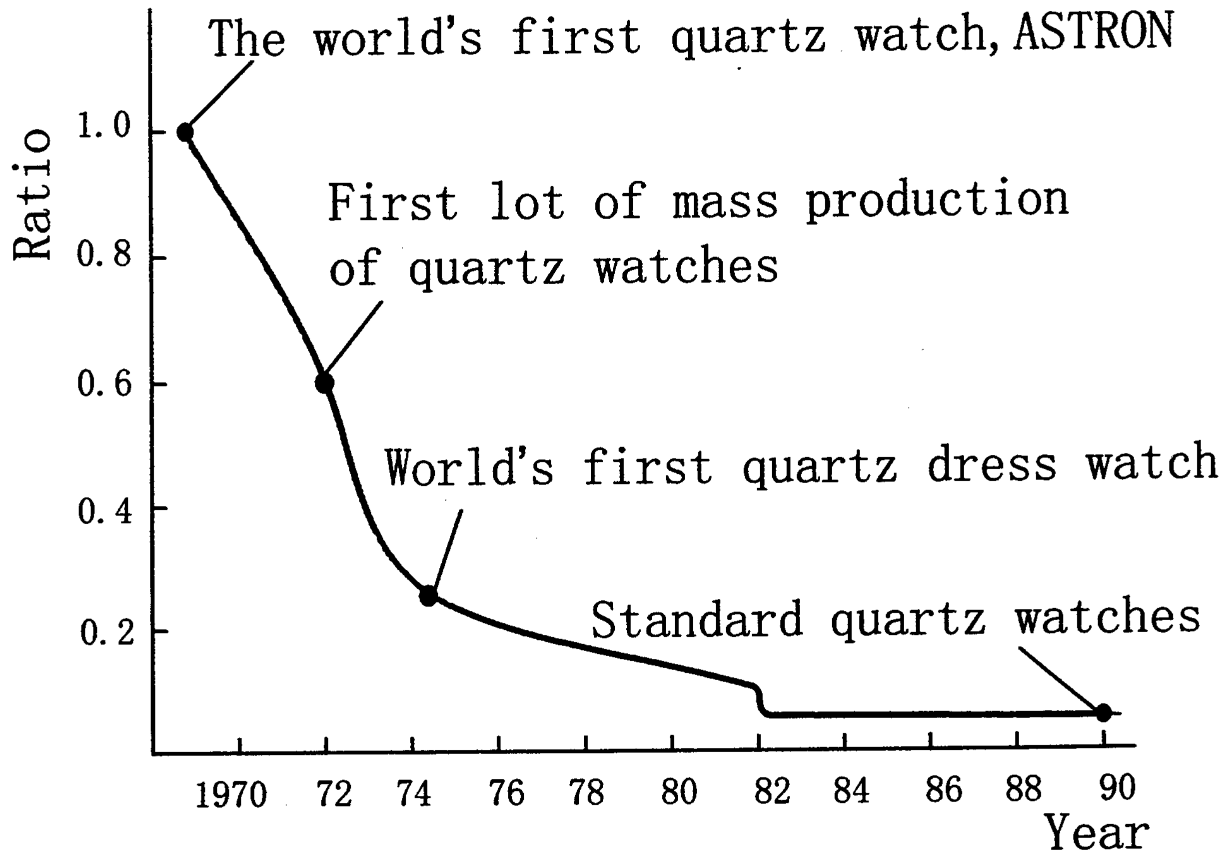
Auto generating system



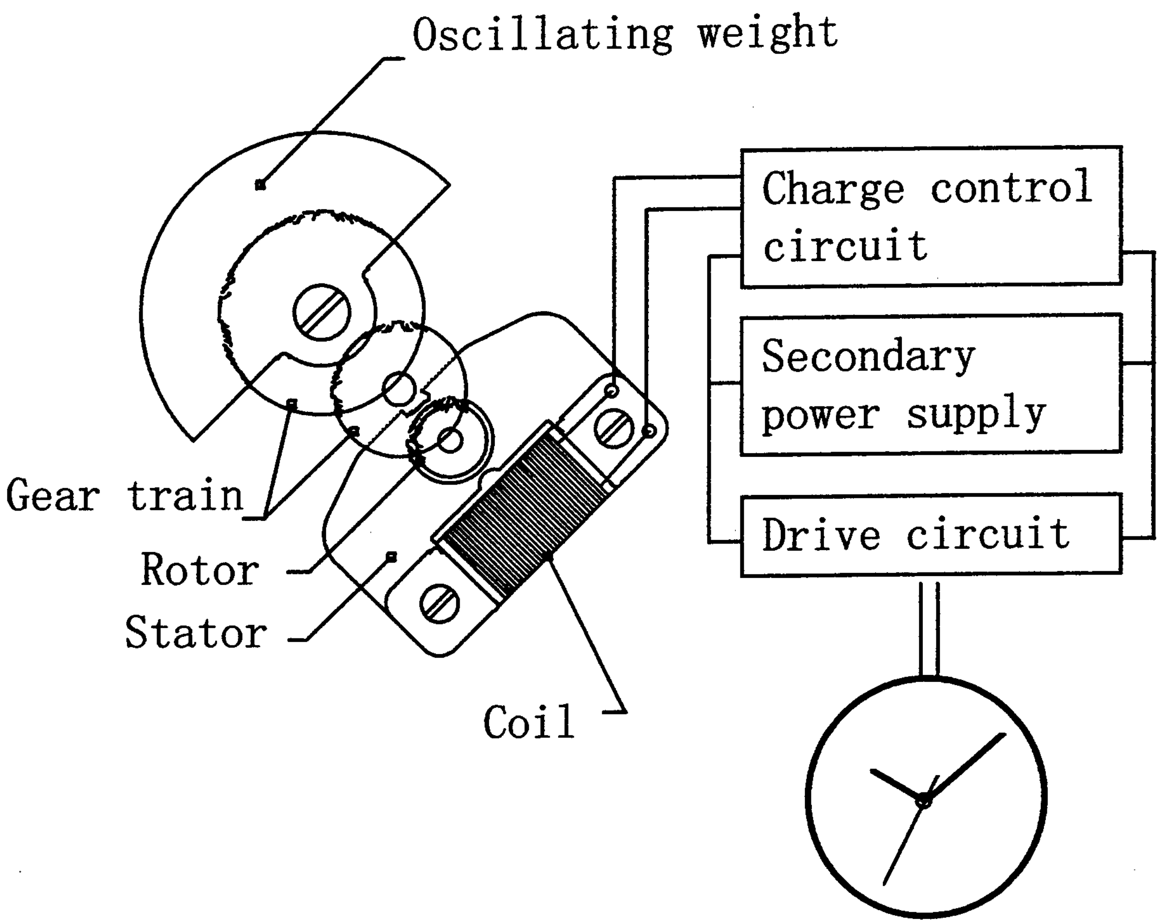


KINETIC

EPSON CORPORATION



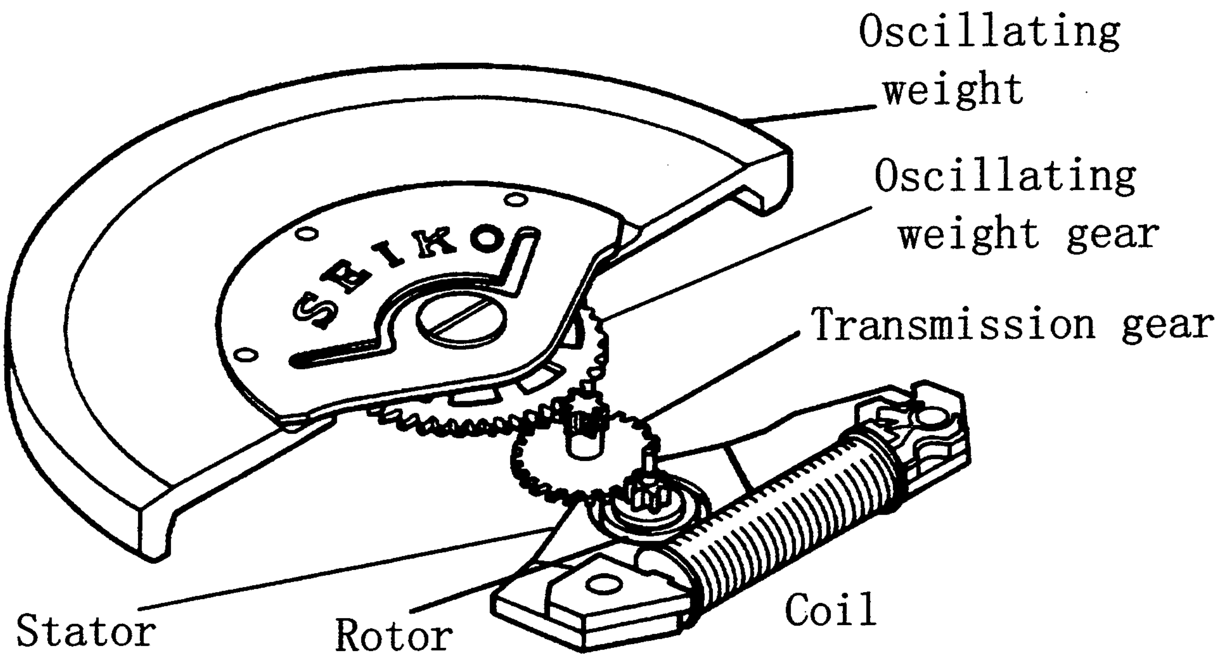
Trend in electrical current consumption
(Seiko Epson data)



AGS outline diagram

Movement Specifications

Type	5M	3M	4M
Outer diameter (mm)	ϕ 27.0	ϕ 23.3	ϕ 25.6
Thickness (mm)	4.3	4.2	2.7
Volume (mm^3)	2.57×10^3	1.90×10^3	1.48×10^3
Rotor magnet	Sm_2Co_{17}	←	←
Oscillating weight	Heavy metal (tungsten)	←	←
The number of coil turns	3700	3900	3600
Accelerating ratio	94.6	93.9	95.2



Oblique view

$$e = -N \frac{d\phi}{dt}$$

e : Inductive-emf

N : The number of coil turns

ϕ : Flux

t : Time

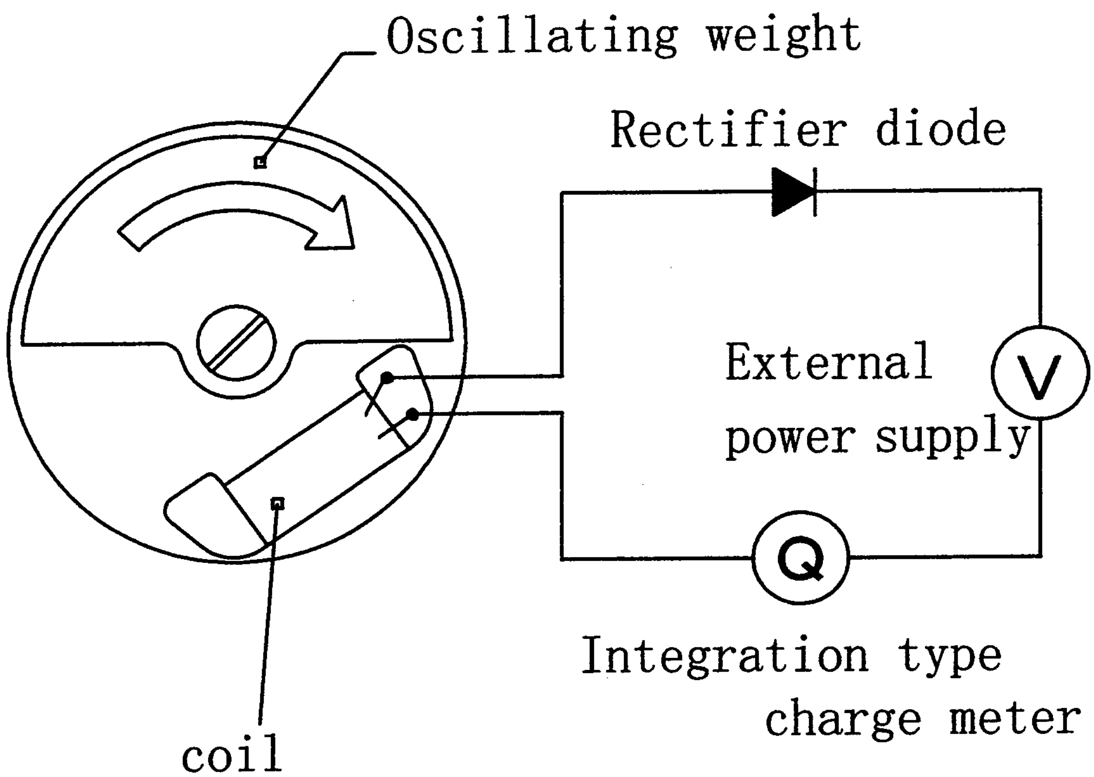
$\downarrow$

N : 3500~4000 Turns

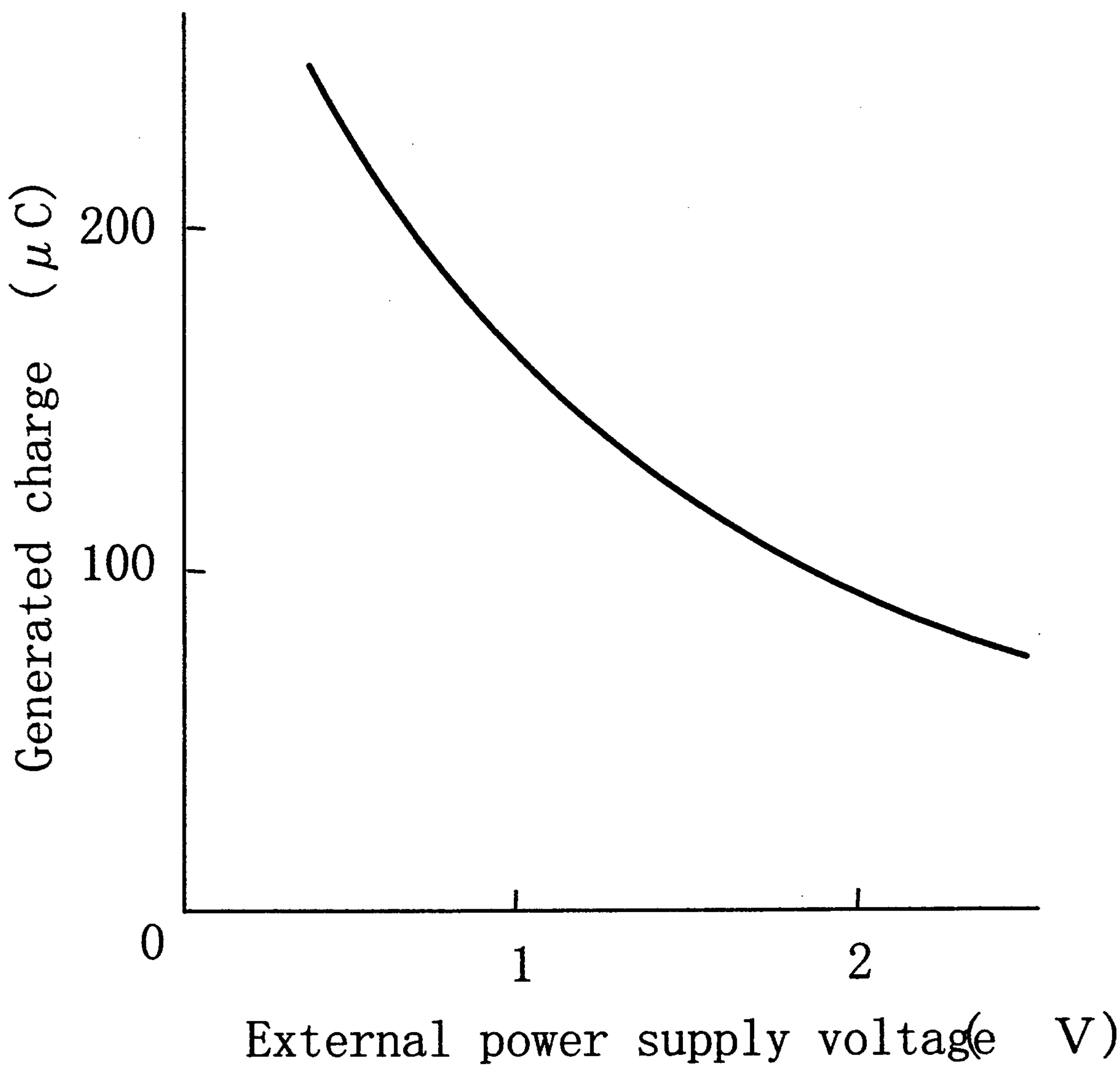
ϕ : Rare earth magnet (Sm_2Co_{17})

Accelerating ratio : 90~100 Times

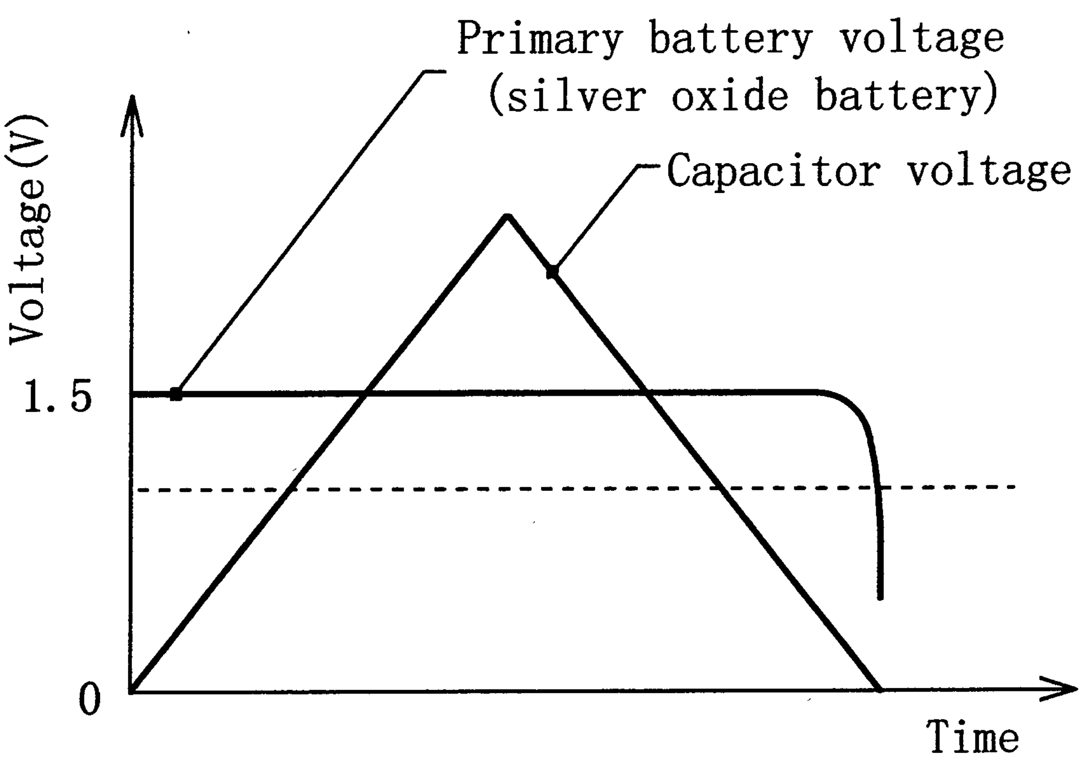
Inductive-emf



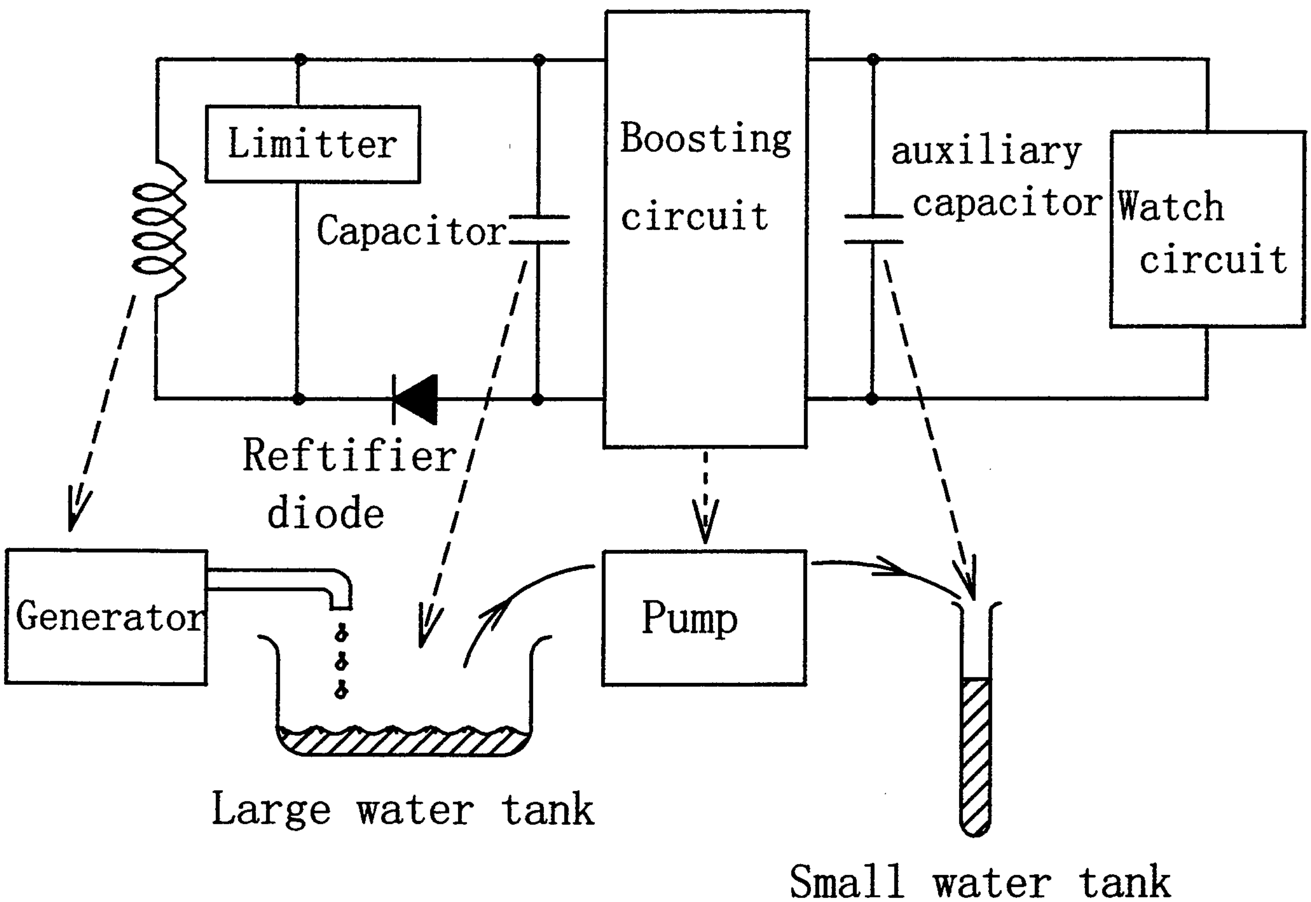
Generated charge measurement



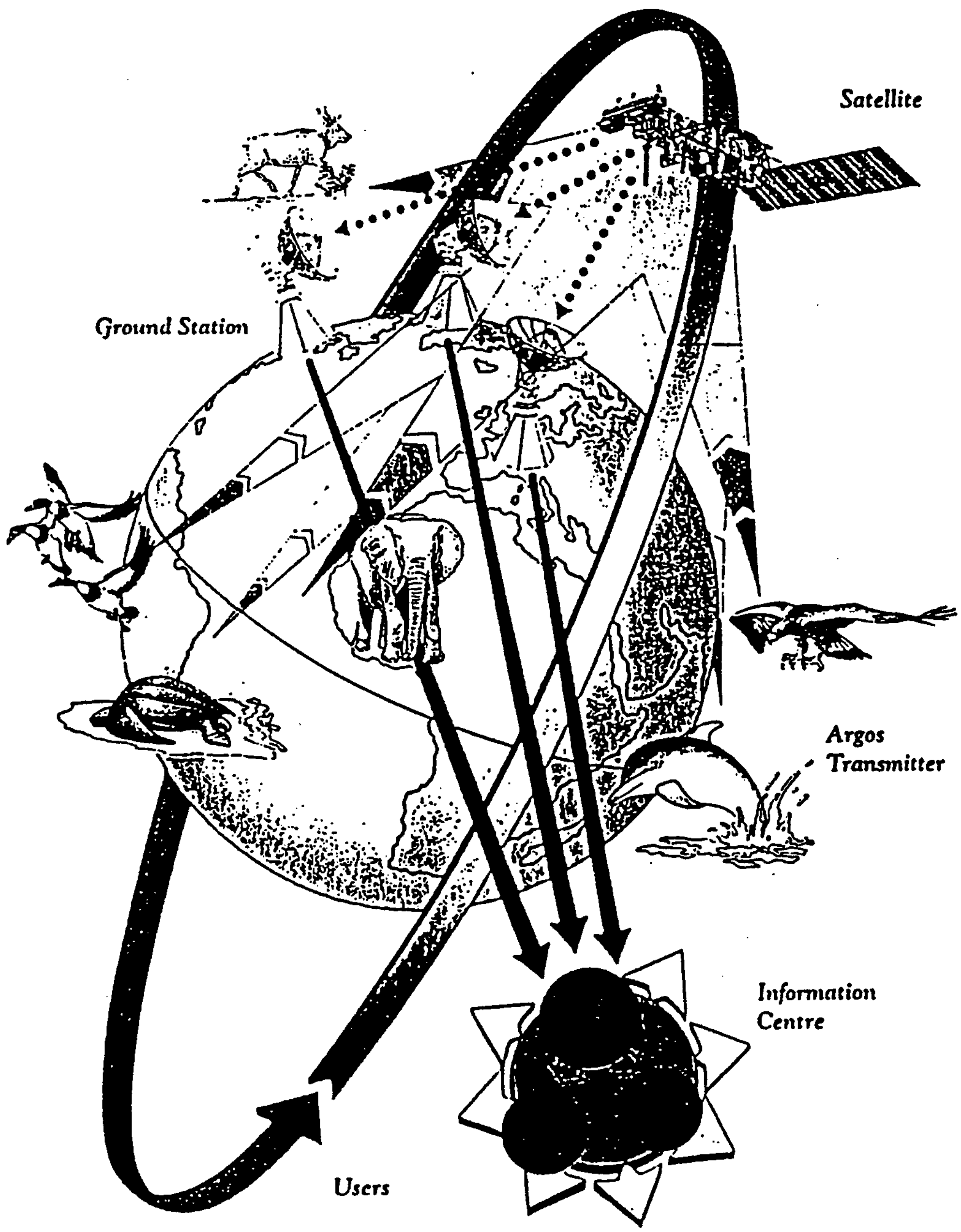
Generated charge



Comparision of power supply voltage

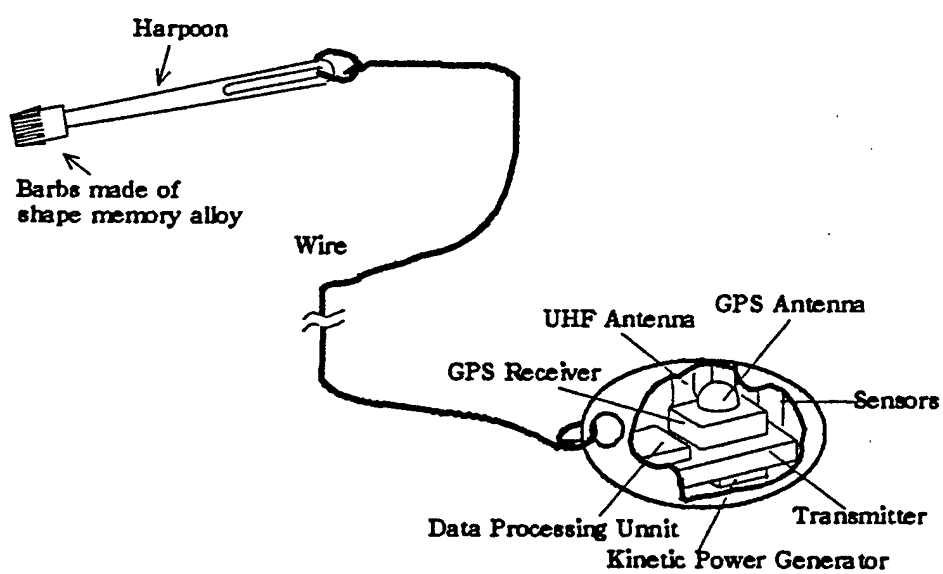


Boosting drive system outline diagram

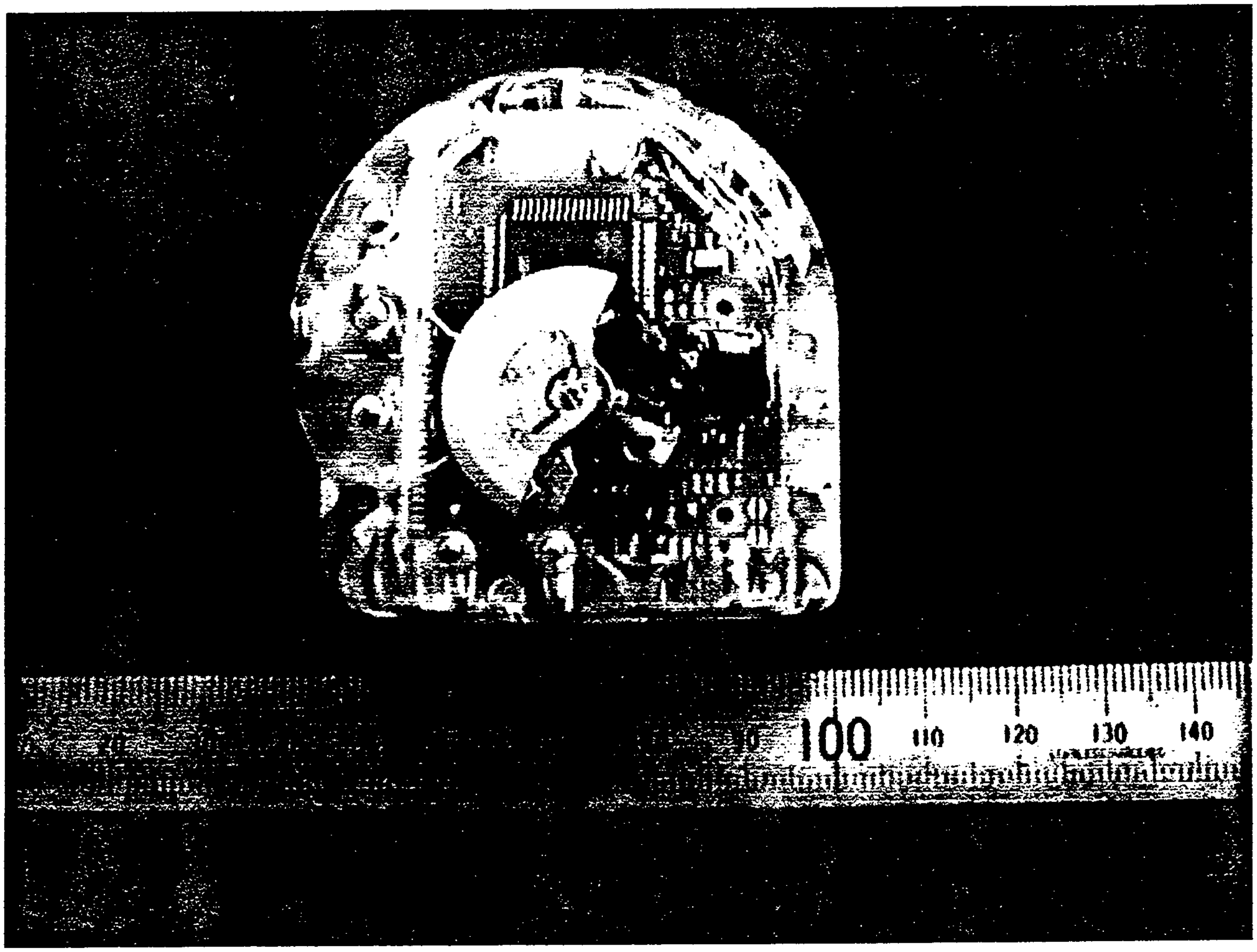

Satellite
Ground Station
Argos
Transmitter
Information
Centre
Users

Major characteristics of probe

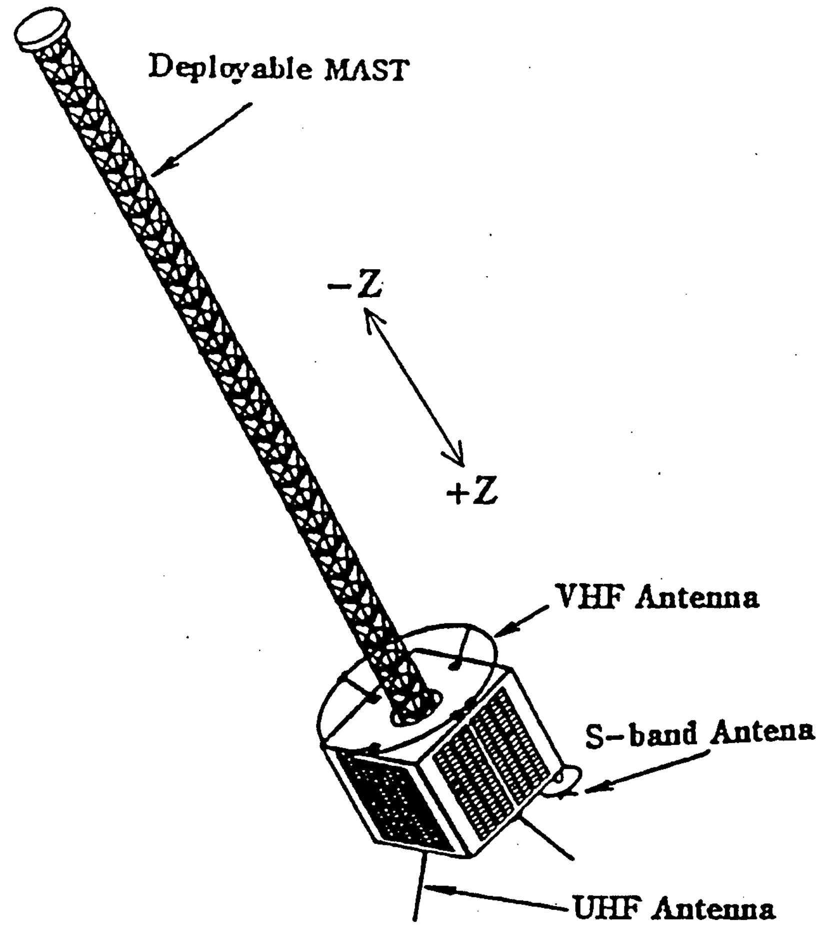
Mechanical Characteristics	
Shape;	Football shape
Dimension;	Long axis·····30 cm Short axis····15 cm
Weight;	10 kg
Power system	
Generating power;	2 W
Power generator;	Kinetic power generator
Telemetry system	
Uplink frequency;	UHF
Uplink modulation;	1200 bps Manchester-code/PM
Sensor system	
GPS receiver;	
Geomagnetic field sensor(Flux gate type),	
Water pressure sensor;	
Thermometer;	
Acoustic sensor;	

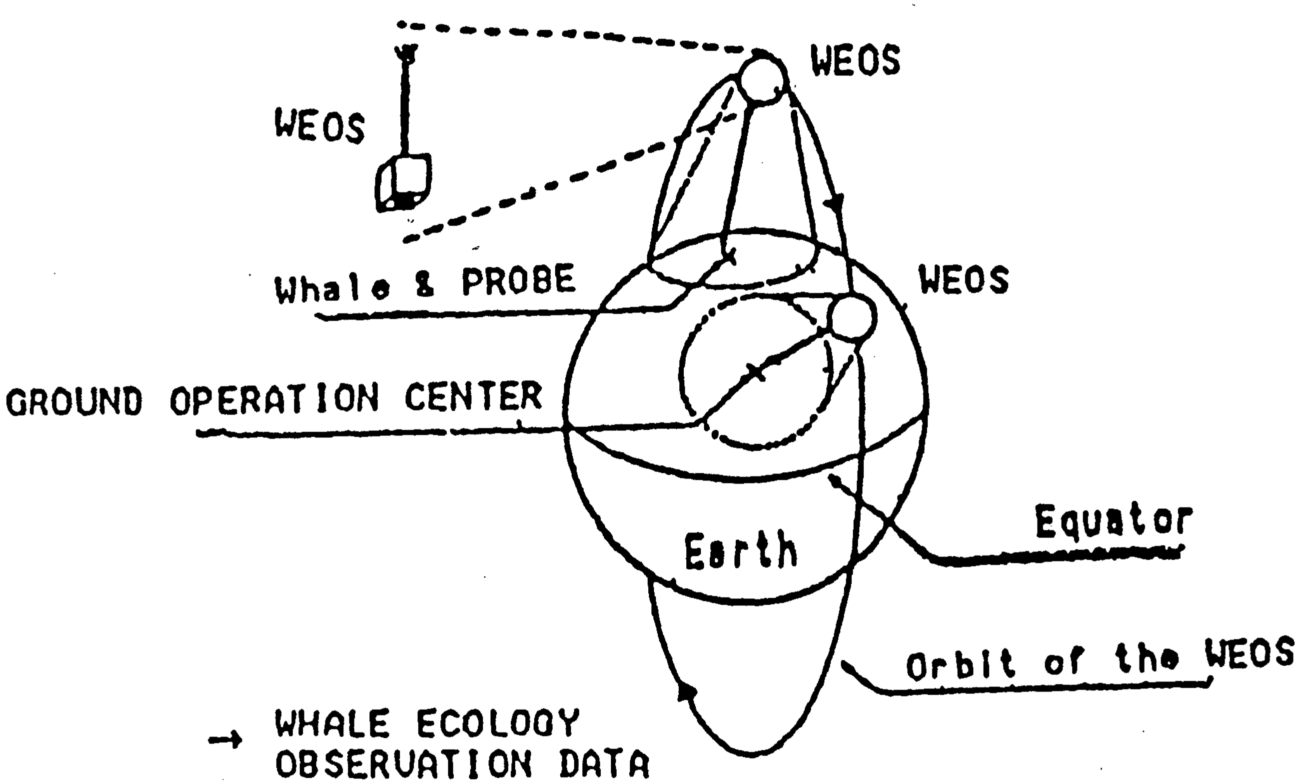


Exrternal View of Probe



AGS application


Deployable MAST
-Z
+Z
VHF Antenna
S-band Antena
UHF Antenna


WEOS
WEOS
Whale & PROBE
WEOS
GROUND OPERATION CENTER
Equator
Earth
Orbit of the WEOS
→ WHALE ECOLOGY
OBSERVATION DATA

WEOS

"OVERVIEW OF DEVELOPMENTS IN SOUTH AFRICA"

(UNAVAILABLE)

Mr. Etienne Rijkheer

SYZYGY
Capetown, South Africa

"TECHNOLOGICAL CHALLENGES FOR HUMAN POWERED SYSTEMS"

Mr. J. Eric Tkaczyk

General Electric Corporate Research and Development
Schenectady, New York

GE Research
& Development Center

Technological Challenges for Human Powered Systems

presented at the

Prospector IX

by

J. Eric Tkaczyk

General Electric Corporate Research and Development

Outline

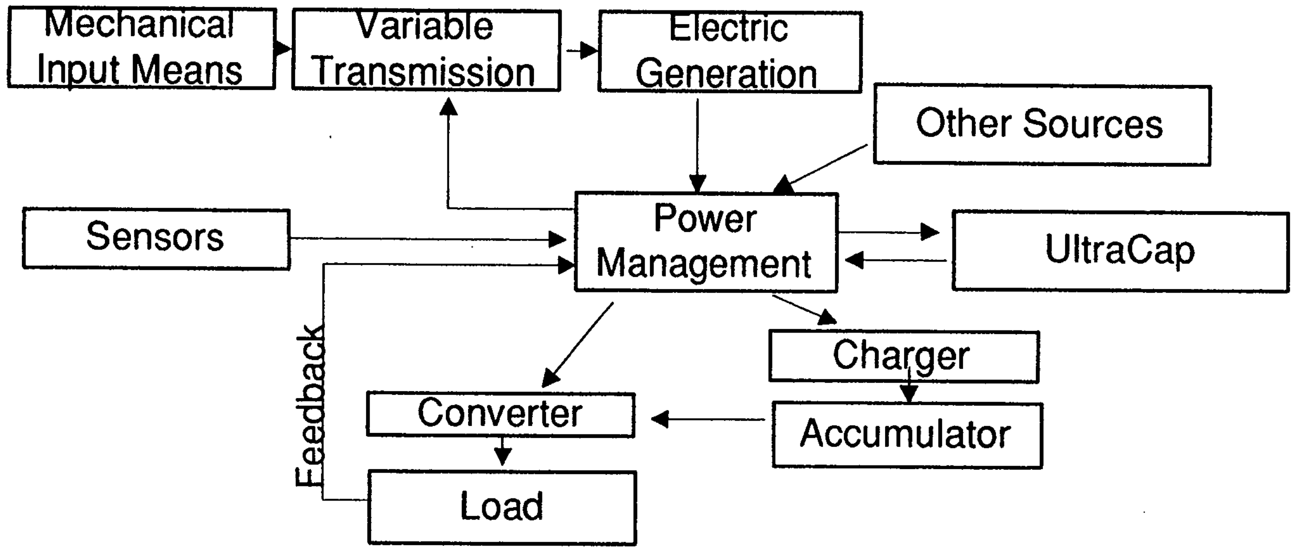
Strategy for an adaptable power system

Technologies:

- mechanical to electrical conversion
- energy storage tradeoffs
- voltage conversion benefits
- packaging to minimize perceived effort

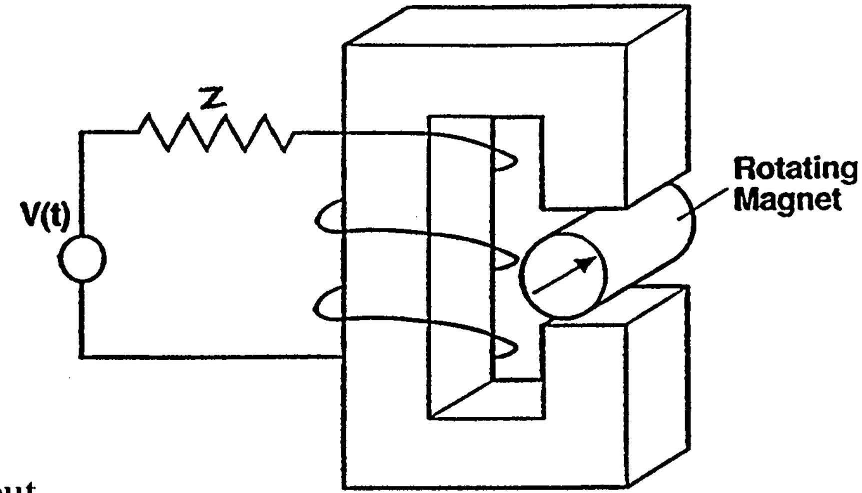
Advancing the state of the art

Human Powered Systems:



- efficient, reliable, adaptable
- minimum perceived effort
- variable frequency and duty cycle
- diverse load requirements
- adverse environmental conditions

Mechanical to Electrical Conversion



$V = Iz + n\, d\Phi/dt$

Input Power — torque constant — Output Power

$$\tau_s\omega = \tau_0\omega + \rho\omega^3 + k_B I\omega = \tau_0\omega + \rho\omega^3 + VI + I^2 z$$

losses — linear — quadratic — ohmic

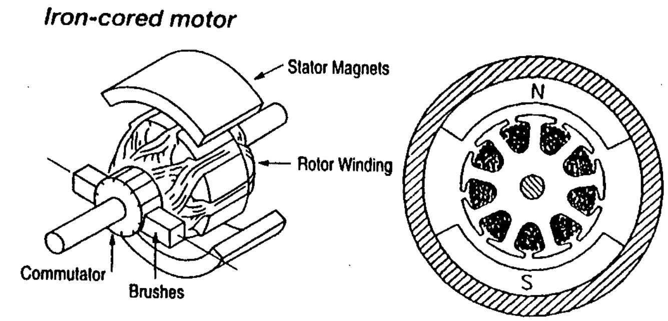
efficiency

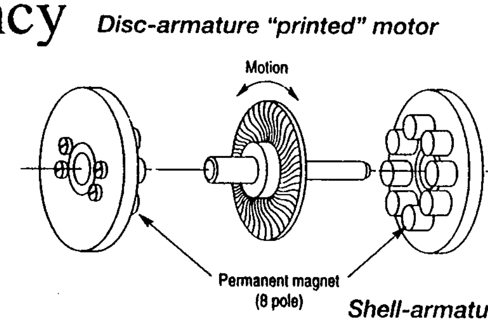
$$\eta = \frac{IV}{\tau_s\omega} = \frac{1 - \tau_0/\tau_s}{1 + z/R}$$

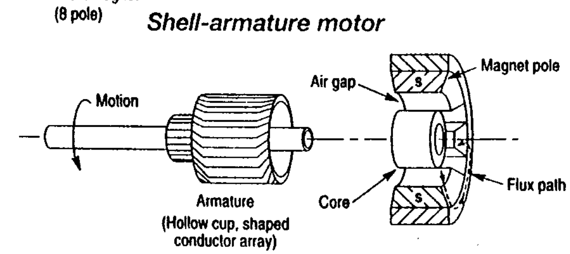
Generator Construction Tradeoffs

$$V = k\omega = (pn\,\Phi)\,\omega$$

poles   # turns   flux   frequency



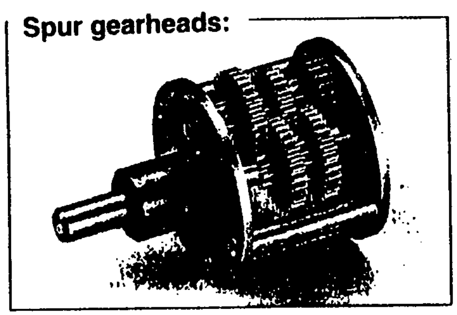


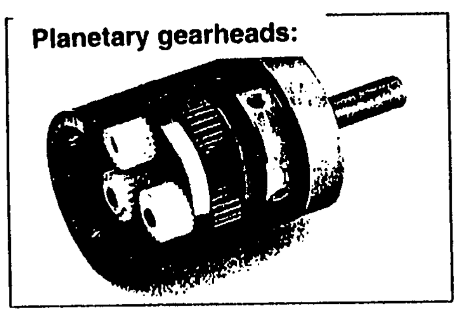


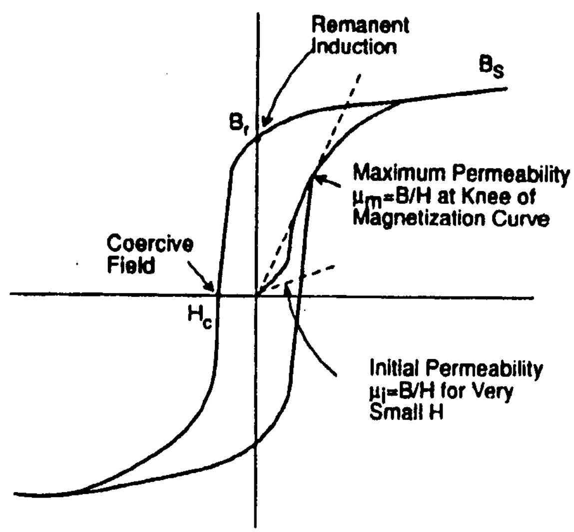
n--> resistive losses

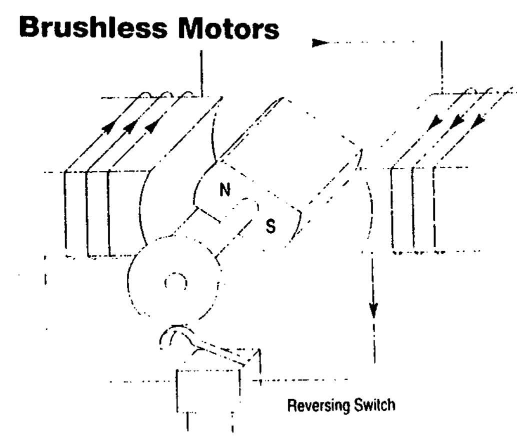
Φ--> hysteresis losses~ B^2

ω--> frictional losses



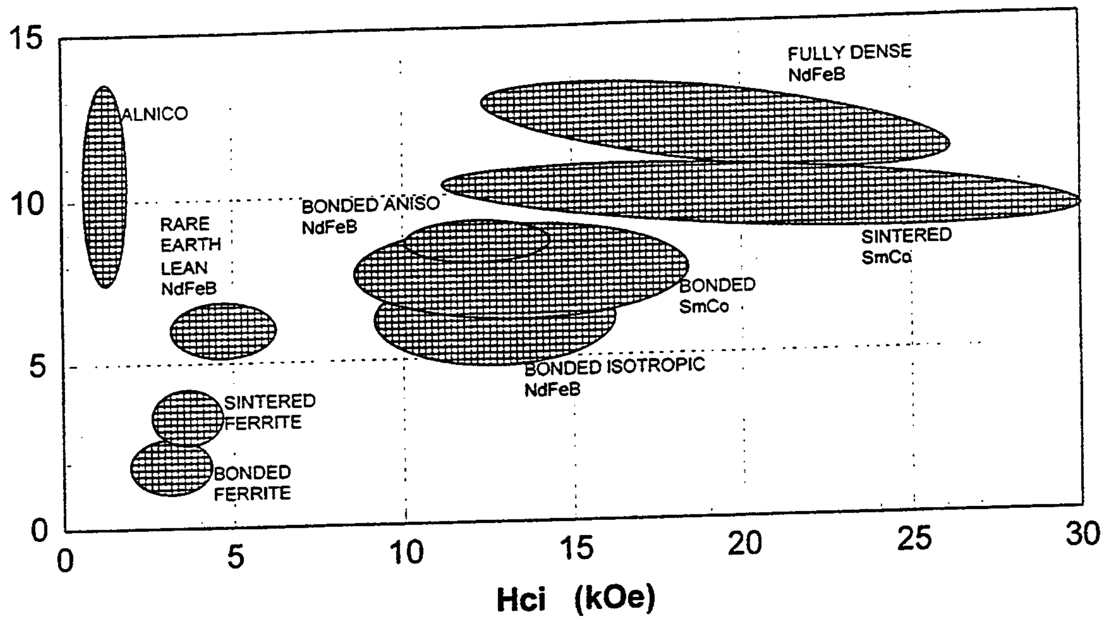




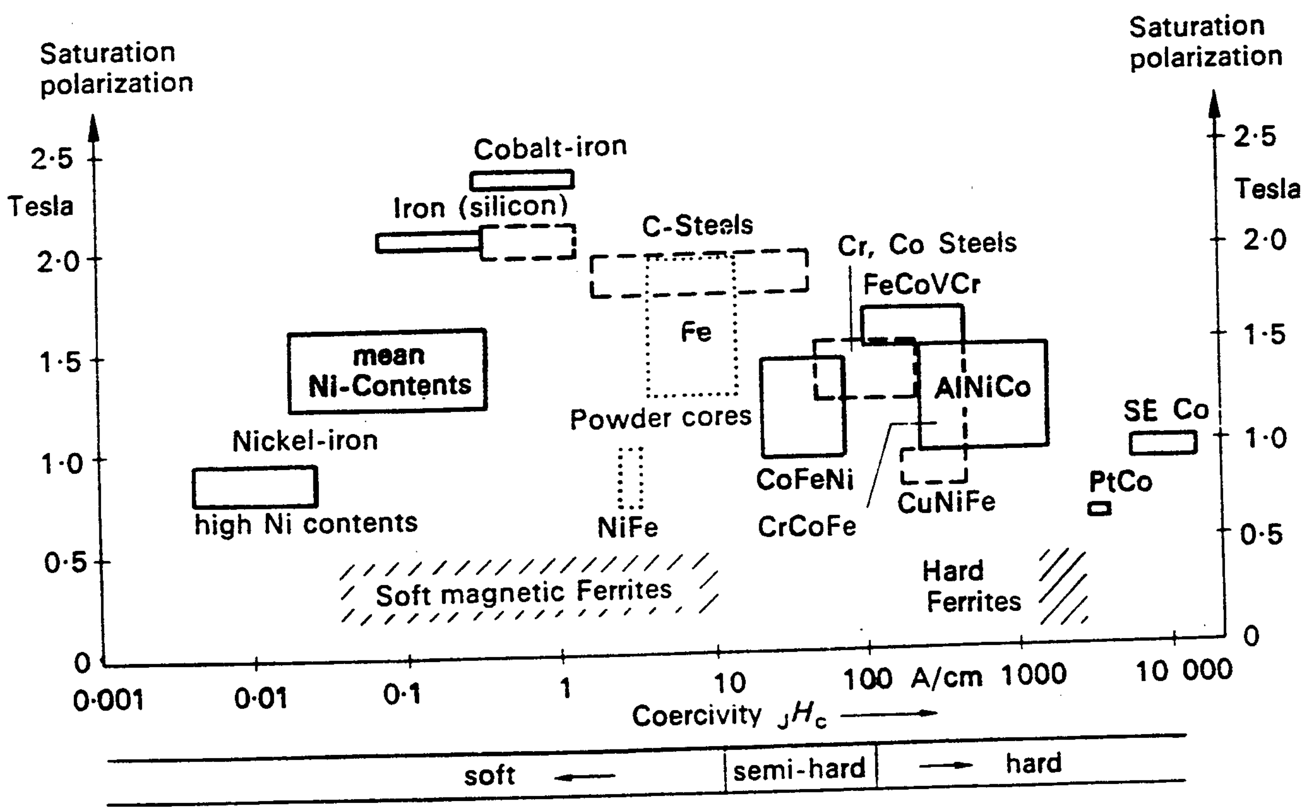


TYPICAL MAGNETIC PROPERTIES

OF COMMON PM MATERIALS

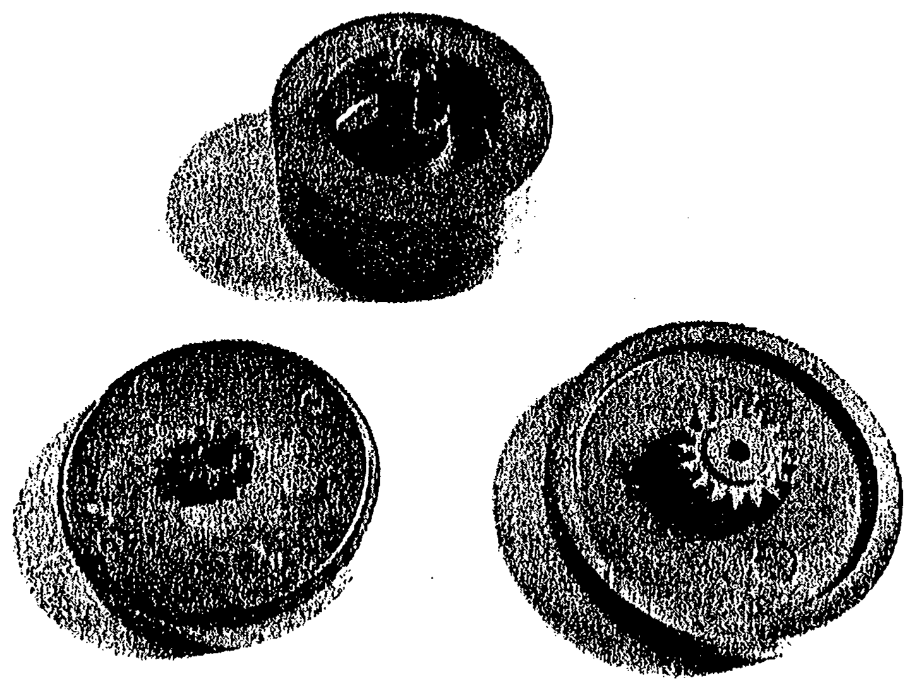


ARNOLD
THE ARNOLD ENGINEERING COMPANY



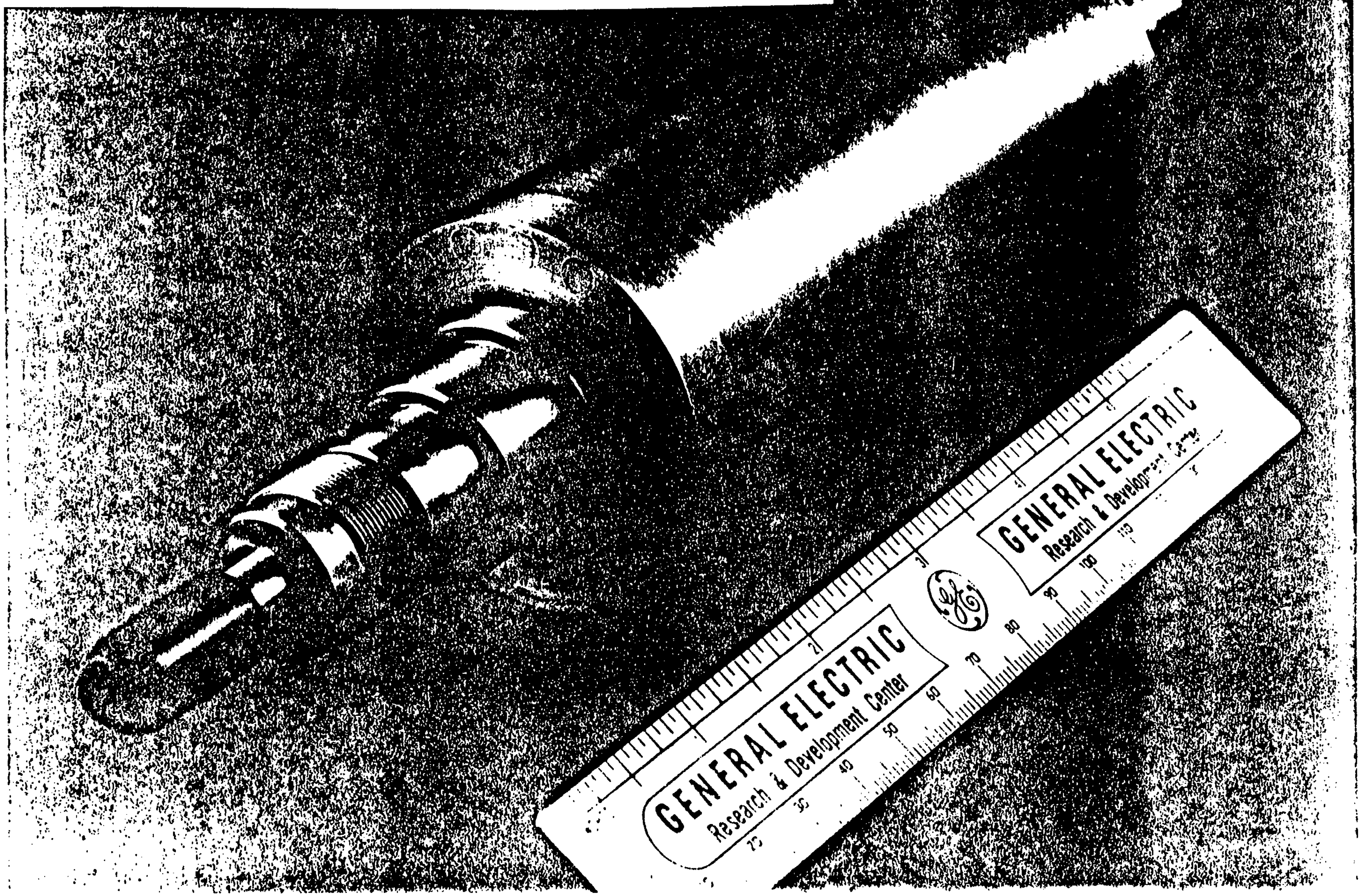
Bonded Magnet Technology:
Integration of Magnet and Gear Elements

WIDIA



High Speed Rotor:

optimized for both magnetic and mechanical performance
high-strenght conductor (Glidcop: $Cu+Al_2O_3$)
special heat treatment for Si-Fe lamination strength

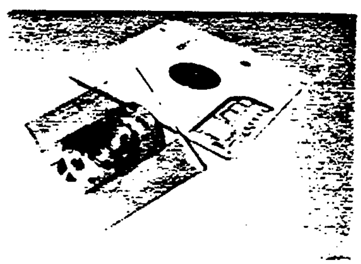


David Howe, University Sheffield, England

Case Study - Micro-Generator for 'Smart Diskette'

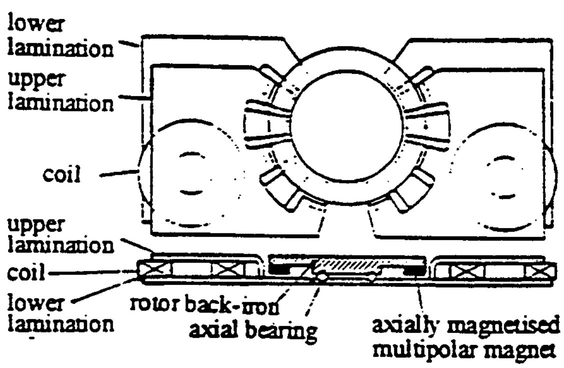
A permanent magnet generator had to be designed to fit within an overall space envelope of 70mmx34mmx3.3mm and be capable of supplying a min. current of 20mA at 5Vdc.

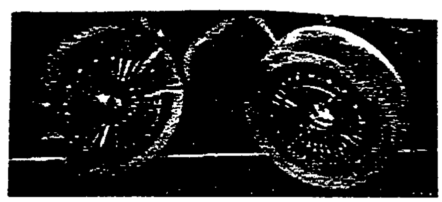
Generator Topology



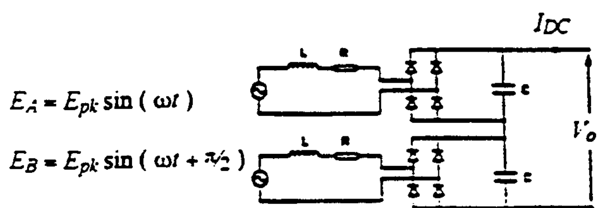
- The preferred topology is a 2-phase machine with a 32-pole axially magnetised sintered NdFeB magnet and cobalt steel laminations

- The magnet flux is focused to two concentrated coils.





Rectification/Smoothing Circuit



- Of the various possibilities a series connection of the rectified and smoothed outputs is the most efficient.

Design Optimisation

Coil flux = 1.7e-05 Wb
Coil permeance = 4e-07 Wb/A
Coil OD = 0.019 m
Coil ID = 0.006 m
Coil thickness = 0.0022 m

Number of turns ⇨

Capacitance (F) ⇩	600	650	700	750	800	850	900	950	1000
1e-06	[illegible]	[illegible]	[illegible]	7.30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2e-06	5.00	7.30	[illegible]	14.30	[illegible]	17.50	17.00	18.30	[illegible]
3e-06	8.30	12.00	16.30	18.00	[illegible]	19.00	19.30	[illegible]	[illegible]
4e-06	[illegible]	15.30	18.00	19.30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5e-06	[illegible]	16.00	18.00	[illegible]	[illegible]	[illegible]	18.30	17.00	17.30
6e-06	[illegible]	16.00	17.00	[illegible]	18.30	17.00	17.30	17.00	16.00
7e-06	[illegible]	[illegible]	16.00	17.00	17.00	17.00	16.30	[illegible]	16.30
8e-06	[illegible]	14.00	15.00	16.00	16.00	16.00	16.00	[illegible]	15.30

Maximum load current for 5V output (mA)

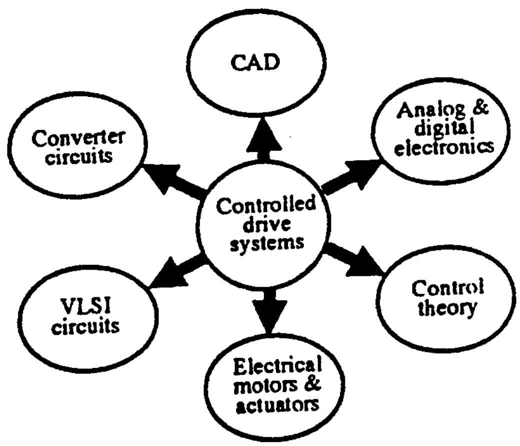
- An optimum combination of number of turns/coil and smoothing capacitance enables max. current to be drawn before output voltage falls below 5Vdc.

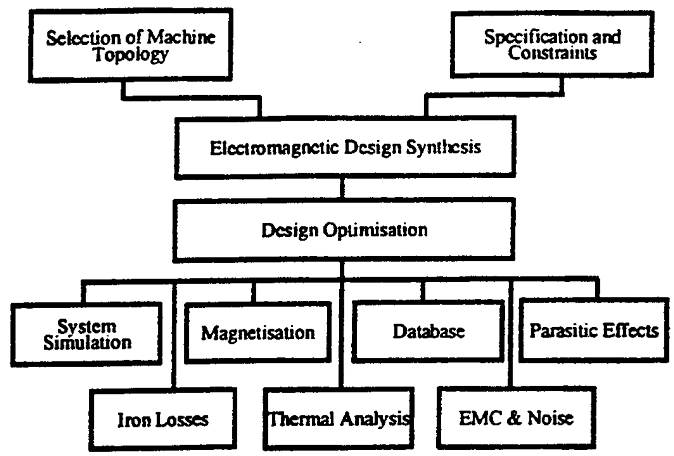
- Optimum values are established by system simulation and determining max. current capability for different combinations of number of turns and capacitance.

Computer-Aided Design

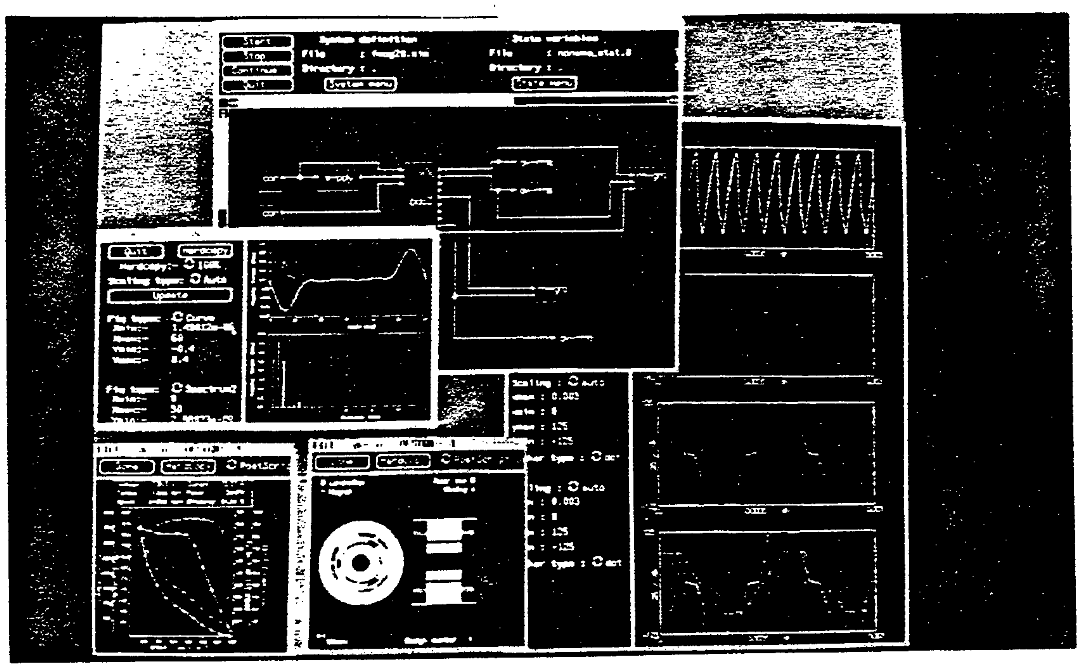
David Howe, University Sheffield, England

Electrical drive systems are a multi-disciplinary technology, with each of the component disciplines developing rapidly. These are creating significant opportunities for meeting the market demand for drive systems with higher performance, improved energy efficiency and better reliability. CAD is also playing a vital role since it allows the merits of alternative drive formats to be assessed on an application-by-application basis, and maximum leverage to be extracted from any grade of permanent magnet. It also permits an integrated design approach, and optimisation at the system level.





CAD can cater for a wide variety of motor/actuator configurations as well as the systems by which they are controlled.



Advanced CAD facilities enable the feasibility of new product concepts to be assessed with confidence.

830112

SAE Technical Paper Series

Elastomeric Regenerative Braking Systems

L. O. Hoppie
Corporate Research Dept.
Eaton Engineering and Research Center
Southfield, MI

ABSTRACT

A theoretical and experimental investigation into the use of elastomers as the energy storage element of a regenerative braking system for urban vehicles is being carried out. This work has included the design and fabrication of full-scale elastomeric energy storage units which were tested to investigate energy density, efficiency and stress-relaxation. A complete small-scale system which simulates a vehicle was tested during transient speed conditions, and a complete full-scale system to be laboratory tested is under construction.

THE PRICE INCREASE OF PETROLEUM-BASED fuel in the past few years has given rise to various research and development efforts for energy conservation. An example of such efforts is aimed at regenerative braking systems for land vehicles. With such a system, kinetic energy is converted t
stored as the vehicle
energy is subsequently
kinetic energy when the
Because a part of the e
pated as heat in the br
accelerate the vehicle,
energy required to pr
reduced.

The prime energy c
system depends on the d
efficiency of the system
a highway truck typical
hundred miles between
little savings even if a
braking system were avai
hand, studies of typica
Federal Urban Driving C

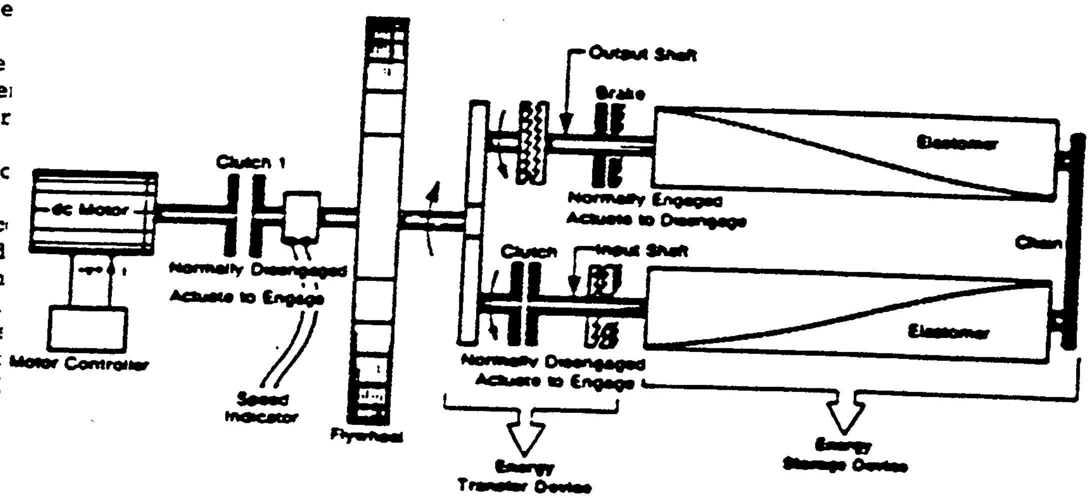
*Numbers in parentheses
at end of paper.

that more than one-third of the energy supplied to the driveline is ultimately dissipated in the brakes. If an ideal regenerative braking system were available, the range per unit of energy measured at the driveline could thus be increased by about 50 percent for this cycle.

Obviously, if there are more stops per mile in a driving cycle, even higher improvements are possible. Consequently, applications such as city buses, delivery vans and subways are particularly attractive for regenerative braking systems.

In order for a regenerative braking system to be cost-effective, the prime energy saved over a specified lifetime must offset the initial cost, size and weight penalties of the system. Consequently, the energy storage unit must be compact, durable and capable of handling high power levels efficiently, and any auxiliary energy transfer or energy conversion equipment must be efficient, compact, and of reasonable cost.

A regenerative braking system based on



0148-7191/83/0228-0112$02.50

Secondary Battery Comparisons:

RECHARGEABLE ALKALINE

Best: Not clear
Worst: Limited cycle life

SILVER ZINC

Best: High reliability
Worst: High cost

LEAD ACID

Best: Mature, Long storage life, Low cost
Worst: Heaviest

NICKEL CADMIUM

Best: Mature, High peak current, Large cycle life
Worst: Heavy, Memory effect

NICKEL METAL HYDRIDE

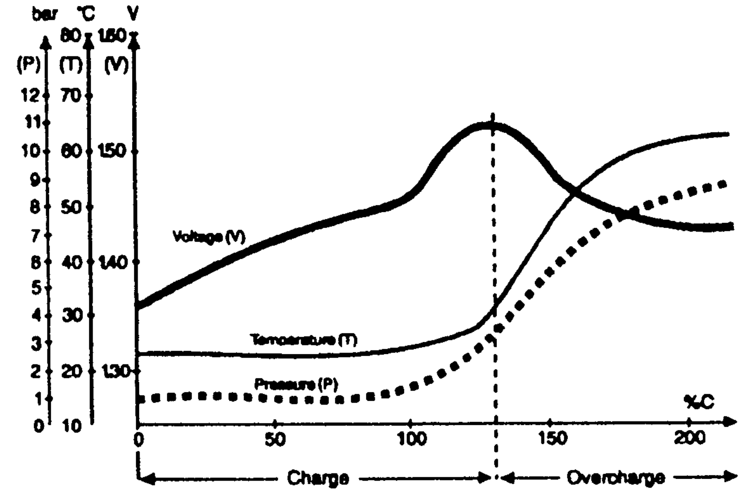
Best: Lighter, Environment safe
Worst: Cost, Self discharge, Complicated charging

LITHIUM

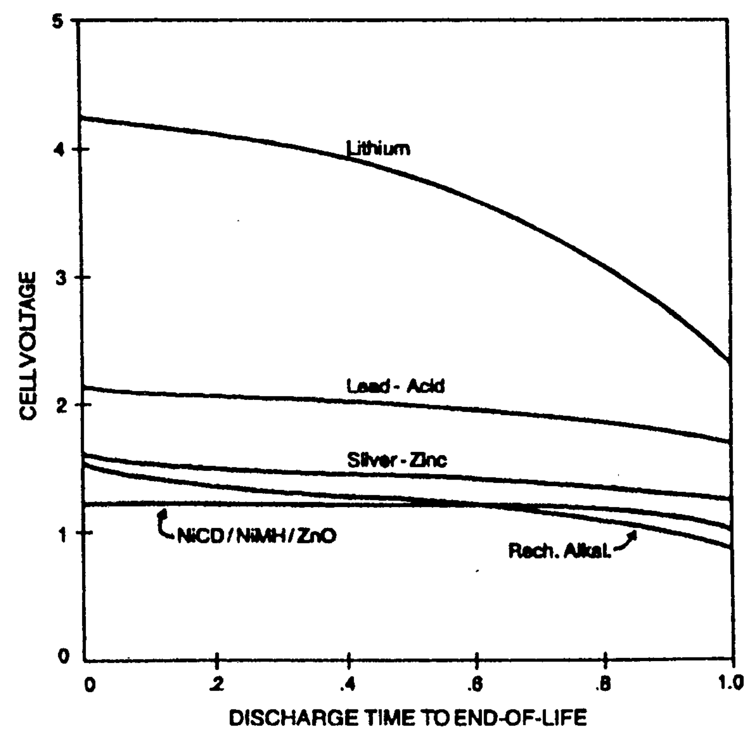
Best: Light weight, High voltage
Worst: Critical charging, Cost

ZINC AIR

Best: Lightest weight
Worst: Not in production



NiCd Charge Characteristics



Normalized Cell Discharge Voltages

AN OVERVIEW OF BATTERY TECHNOLOGIES

RECHARGEABLE BATTERY DATA SHEET

ELECTROCHEMISTRY	UNITS	SEALED LEAD-ACID	PEP-SLA THINLINE	NICKEL-CADMIUM	NICKEL-M/HYDRIDE	RECH. ALKAL.	ZINC-AIR	LITHIUM ION
NOMINAL CELL VOLTAGE	vpc	2	2	1.2	1.2	1.5	1.2	3.7
ENERGY DENSITY								
GRAVIMETRIC (SPECIFIC ENERGY)	Wh/kg	35	46	50	64	76	150	125
VOLUMETRIC (ENERGY DENSITY)	Wh/l	80	110	120	180	219	160	250
CHARGE ACCEPTANCE								
IN-RUSH CURRENT	C amps	7	7	2	1	1	0.04	POOR
TIME TO FULL CHARGE	hours	<4	<4	<1	>1	>3	>24	POOR
OVERCHARGE RESISTANCE								
FLOAT LIFE @ 20°C	years	5-20	8	N/A	N/A	0.5	N/A	POOR
OVERDISCHARGE RECOVERY*								
CAPACITY ON RECHARGE	%	0-90	>90	>90	>90	>90	0	POOR
SELF-DISCHARGE RATE								
% RATED CAPACITY LOST/MONTH @ 20°C	%	2 - 4	3	15	30	0.5	5	5 - 8
% RATED CAPACITY LOST/MONTH @ 40°C	%	8-16	12	60	70	2	20	POOR
CYCLE LIFE (to 80% of rated capacity)								
25% DOD @ C/5 - 2 CYCLES/DAY	cycles	1200	2200	2000	500	100	100	NA
50% DOD @ C/5 - 2 CYCLES/DAY	cycles	600	1000	1000	500	50	50	1000
100% DOD @ C/5 - 2 CYCLES/DAY	cycles	300	500	500	500	25	25	NA
COST PER WATT-HOUR	$/Wh	$0.10-0.60	$0.50-1.00	>$1.00	>$1.50	$0.33	$1.25	>$5.00

*(after discharge to 0 volts and 28 day stand)

Recharge 2-way radio batteries on *your* coffee break!

Two-way radio batteries used to take 16 hours to recharge. And they burned out before the warranty expired. No more. ACT's Ultra-Rapid™ two-way radio battery charger delivers the fastest charge anywhere—*down to an incredible 20 minutes*. And it pumps up battery usable capacity. *Plus, ACT's charger conditions batteries while charging* and delivers full capacity with every charge.

Get ultra performance for your two-way radio batteries. Call 770.582.0001 today.

"We got vast improvement in battery life and increased usable capacity... It also shortened full charges from 16 hours to just under 20 minutes."

— Mike A. Valencia
DOD
(using Motorola Radius)

ACT

The blue box that makes batteries better.

SETTING THE GLOBAL STANDARD FOR BATTERY CHARGING

The Advanced Charger Technology (ACT) process works with the natural chemical processes within the battery to allow the battery to be charged at a maximum efficiency. This charging technology is universally effective on batteries of every major chemistry in wide use today.

Delivery Platforms Available

- Hardware Design, Mfg. and Delivery
- Circuit Board Level Components
- Pre-Programmed Chips
- Software

Products Available

- Ultra-Rapid™ Two-Way Radio Charger

Technology Features

- High Efficiency Charge
- Minimum Battery Heating
- Small Electrode Crystal Structure
- Minimum Battery Gassing
- Advanced, Precise Termination

Technology Benefits

- Prolongs Battery Life
- Ultra-Rapid™ Charge
- Less Energy Usage
- Eliminates Memory Effect
- Higher Asset Utilization
- Environmentally Friendly

The ACT Operating System will provide battery dependent industries with a competitive advantage which will enable their battery powered devices to charge faster, last longer, and perform in a consistent and reliable fashion.

Three Patents Granted

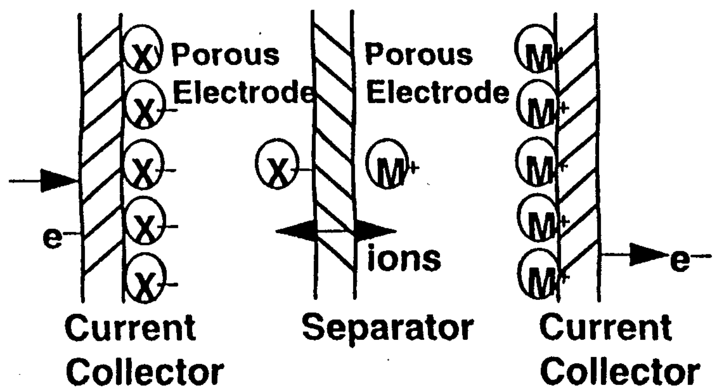
Six Patents Filed

ACT™

0197/1M/PM/MGK
Order Number:CGB02/R1

THE CHARGING STANDARD

Ultracapacitor Technology



$E = 1/2\ CV^2$

	Energy	Power	Time
Electrolytic	V.Low	V. Hi	uS-mS
Ultracap	Lo-Med	Hi	<S->Min
Battery	Hi	Lo-Med	Min-days

Inherent Advantages

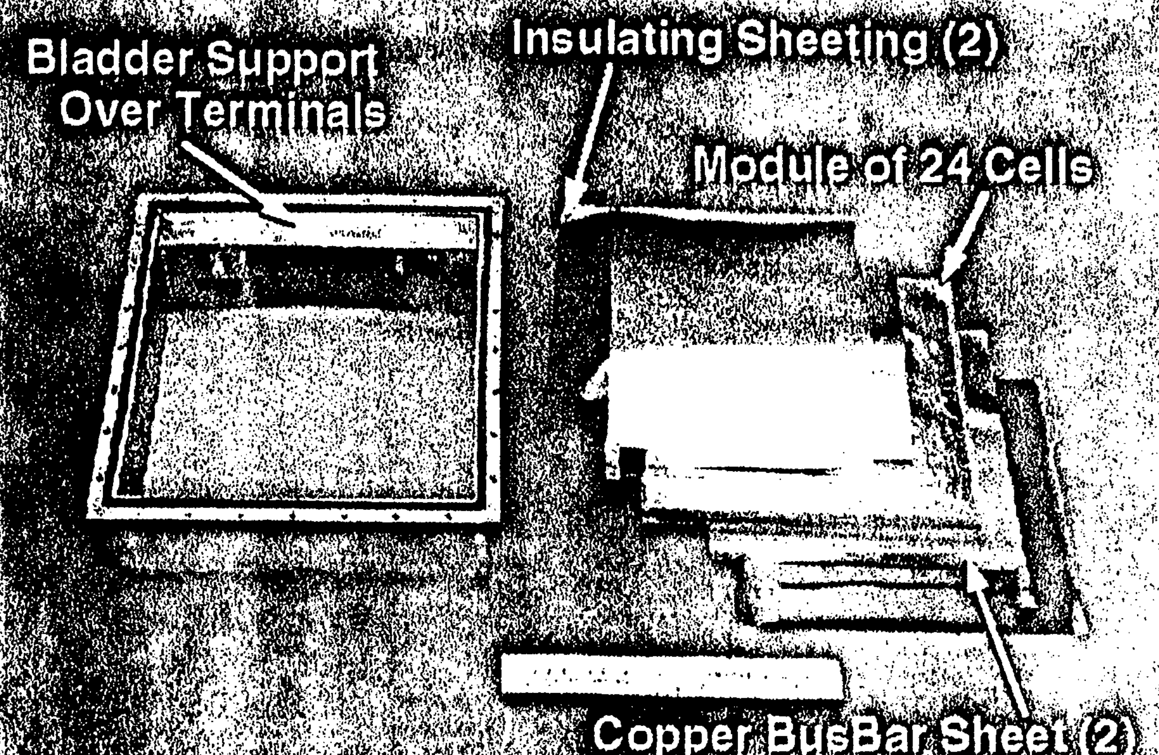
- No Mass transport or chemical changes occur
- Cycle life 100'sK cycles w/o change; only ions move
- Non-polarized - Only magnitude of voltage is limitation
- Environmentally benign while can be low cost

Ultracapacitors: A High Power Source of Energy

Inherent Advantages of Ultracapacitors

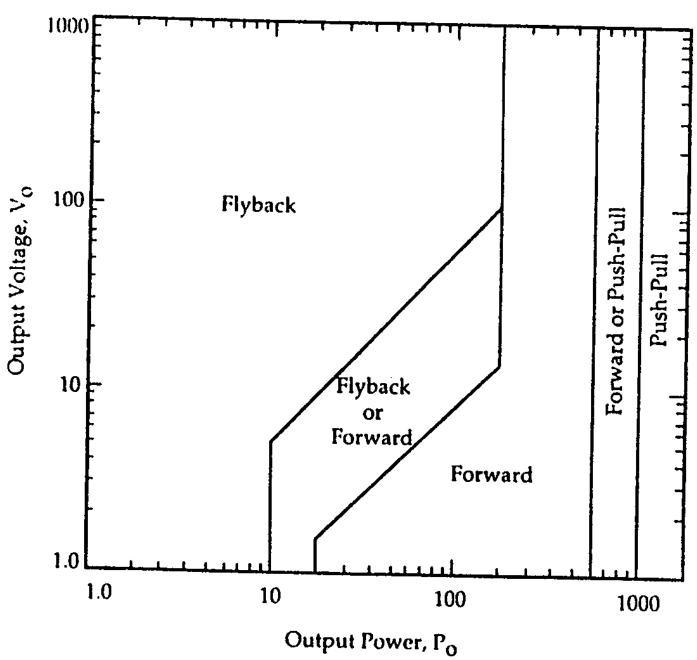
- No change-of-state or mass transport phenomena
- Lifetime not limited by cycling regime
- No low voltage limit
- State of charge accurately found from open-circuit voltage
- Can be charged at same high rate as discharge: recharge time fast
- No maintenance required
- No moving parts
- Little or no ancillary plant
- Modular design is easy and advantageous
- Easily adapted to available space
- Environmentally benign compared to other chemical system
- Low cost materials can be used
- Sealing and packaging less complicated than with other chemical systems

Assembly—First 1000 Watt Stack



Voltage Conversion

- high efficiency
- power management through control circuitry
- design issues: EMI, spikes, ripple content
  short circuit protection
  component tolerances



Converter choice as a function of SMPS output voltage, V_o, and output power P_o.

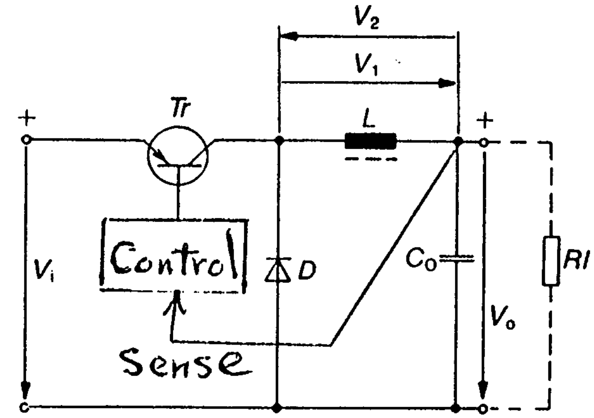


Fig. 1.2 Inductor-coupled step-down converter

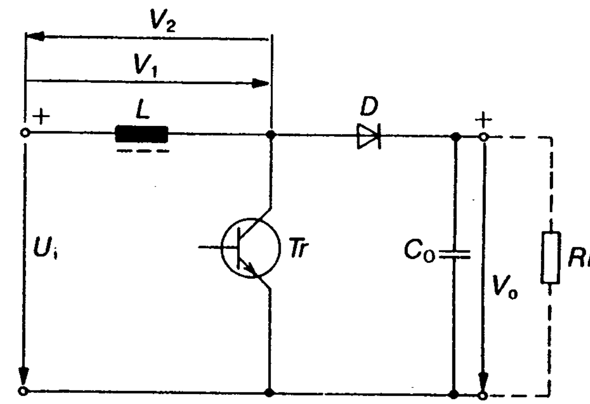


Fig. 1.3 Inductor-coupled step-up converter

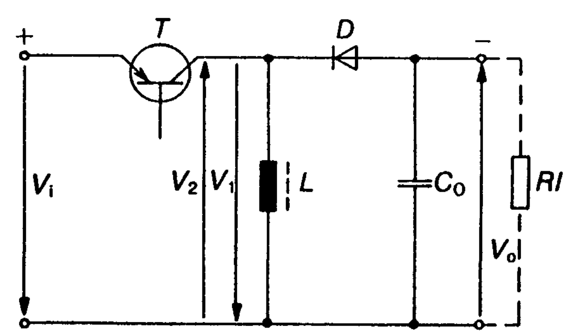
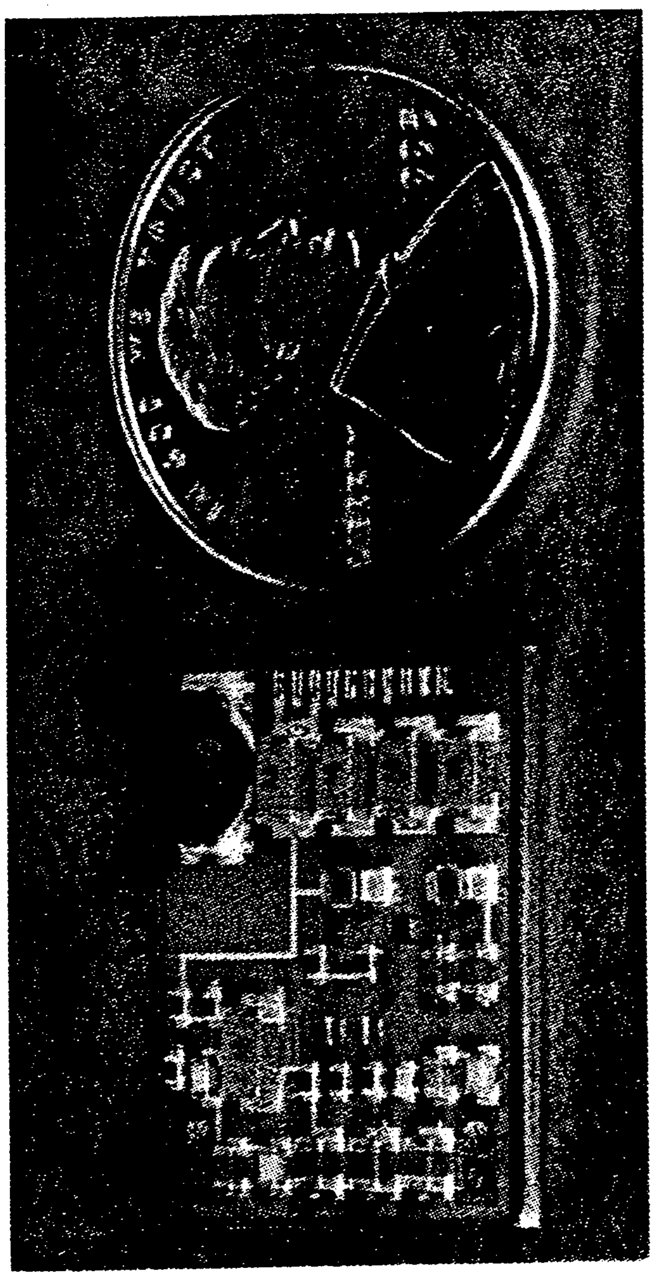
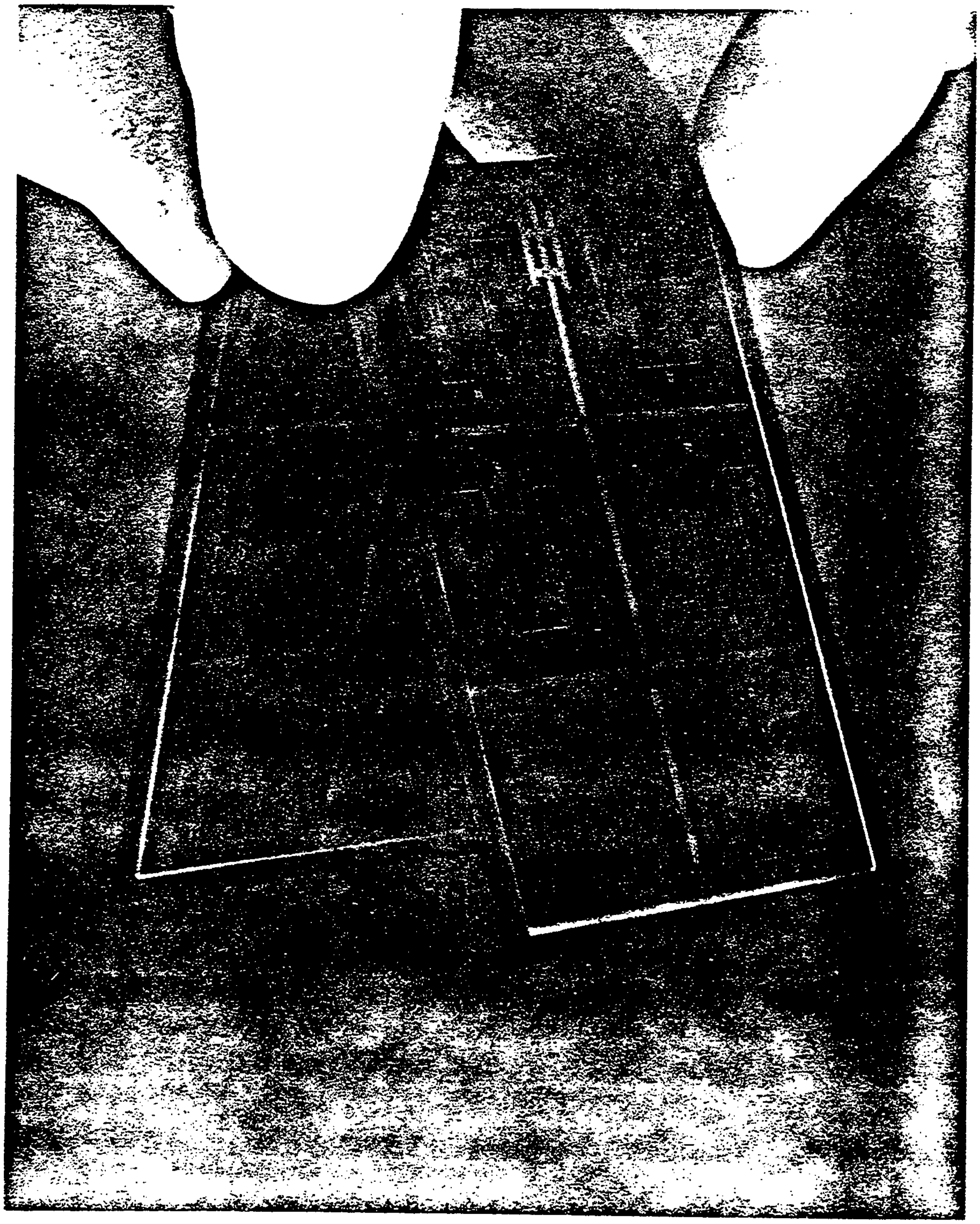


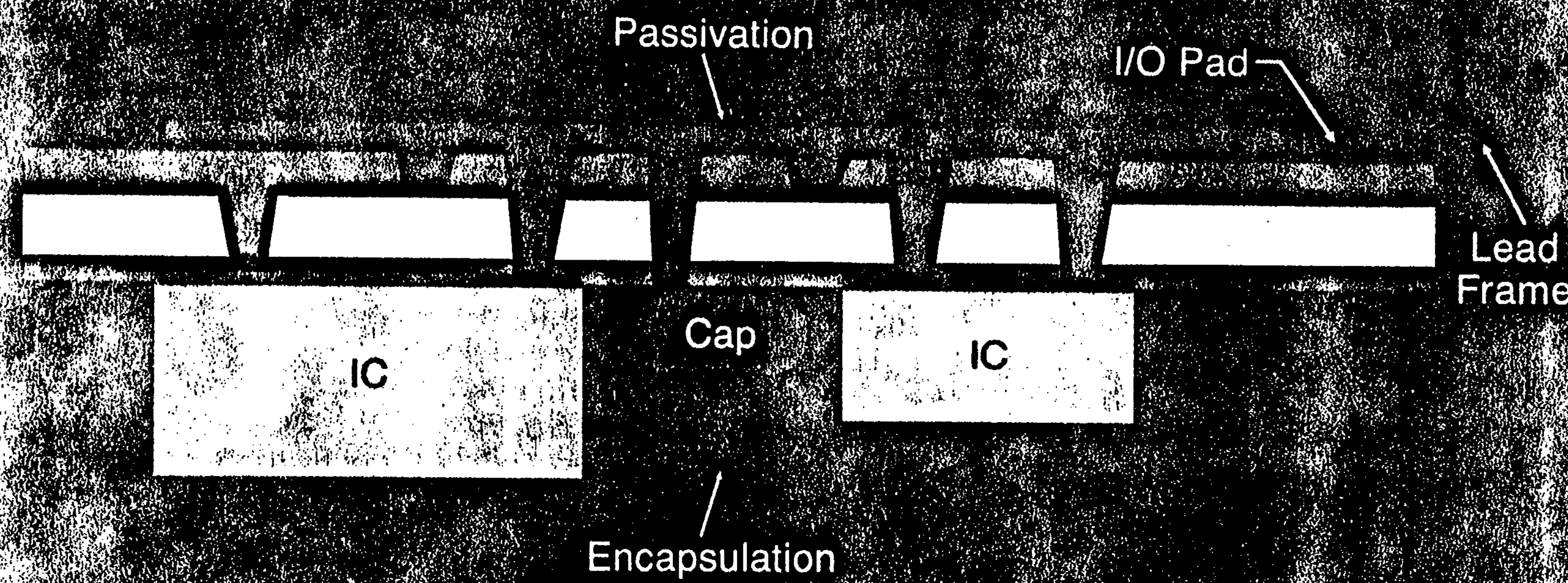
Fig. 1.4 Inductor-coupled flyback converter





COF Advantages

- Chip on Flex:
  - die are fully encapsulated, protected.
  - fully testable while on flex or singulated.
- Fully compatible with standard SMT:
  - pick & place and handling equipment.
  - batch reflow solder processes, chemicals, temperature.
- Can use die from any source:
  - perimeter or area array.
  - Al or Au or any pad metal system.
- Standard I/O array configurations:
  - not effected by die shrinks.
  - not effected by switching vendors.
- Applicable to wide range of chip complexities:
  - from three terminal transistors to more than 400 I/O chips.
  - for RF, logic, power, analog and electro/optical.
- Low cost, simple, robust process.

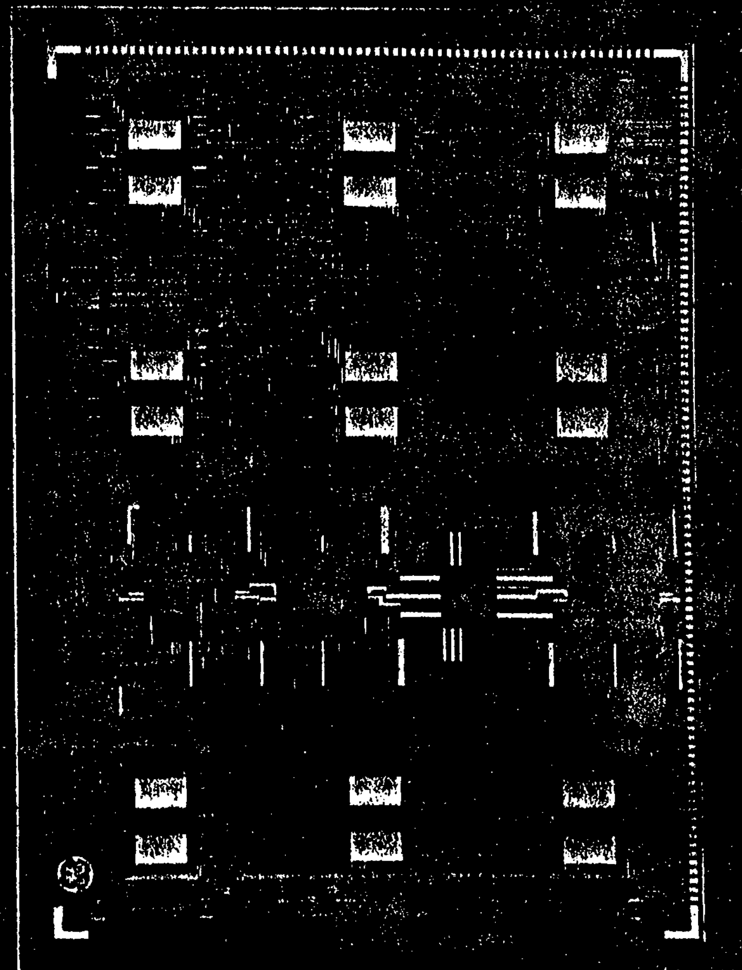


Chip-on-Flex Multichip Module Cross-Section
With Top Mounted Lead Frame

SANDERS
A Lockheed Martin Company

Corporate Research & Development

HPSC DRAM Module



Module Features:

Memory Configuration: 8 Mbyte x 32

Parity Error Detection

Typical Power: 10W @ 5V

Low Cost Chip on Flex Technology

Module Size: 2.496" x 1.796"

I/O - 157

Parts:

Qty	Type	Function
18	DRAM	Memory
3	ISPLSI1032	DRAM Controller
1	PAL22V10	DRAM Controller
9	180 nf	Capacitors

Total: 31

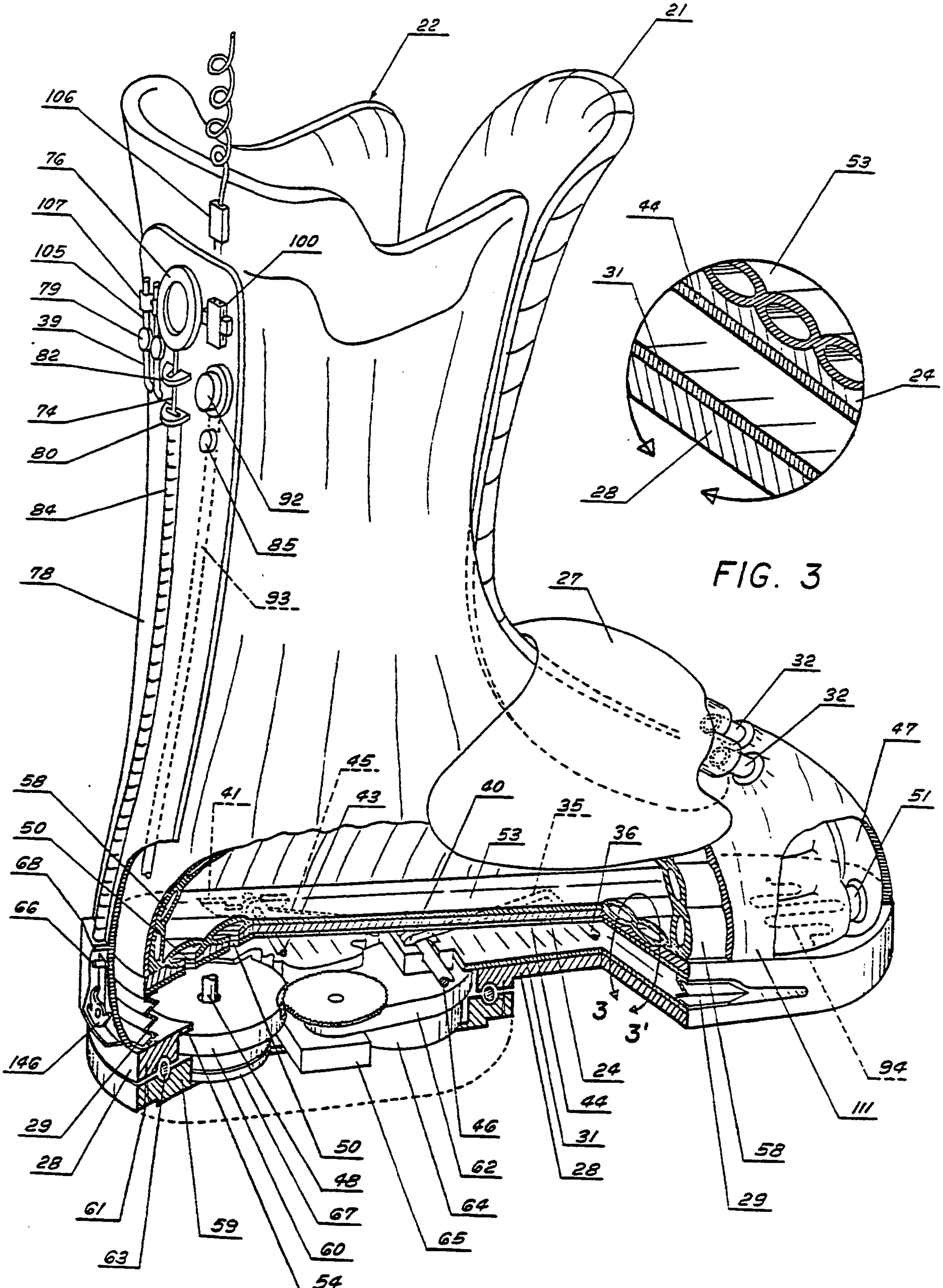

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FIG. 3

FIG. 2

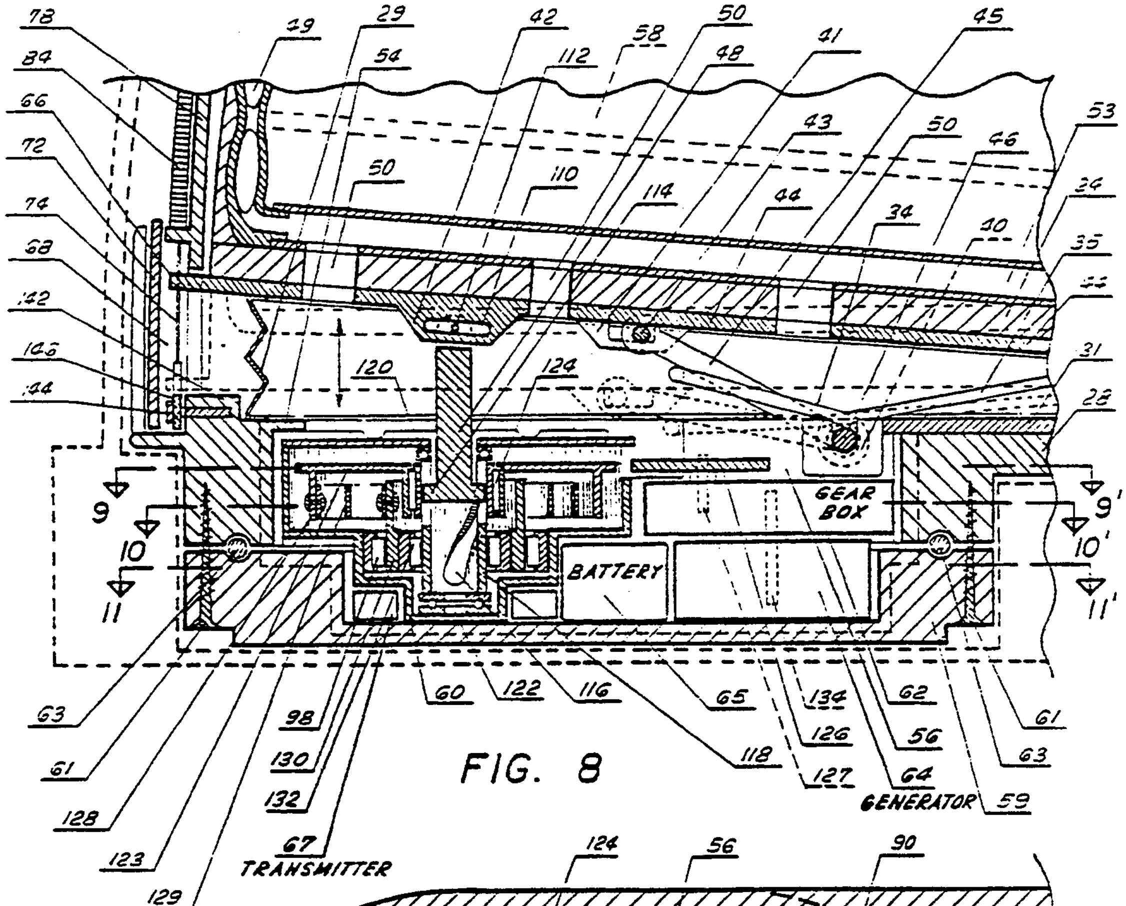

FIG. 8

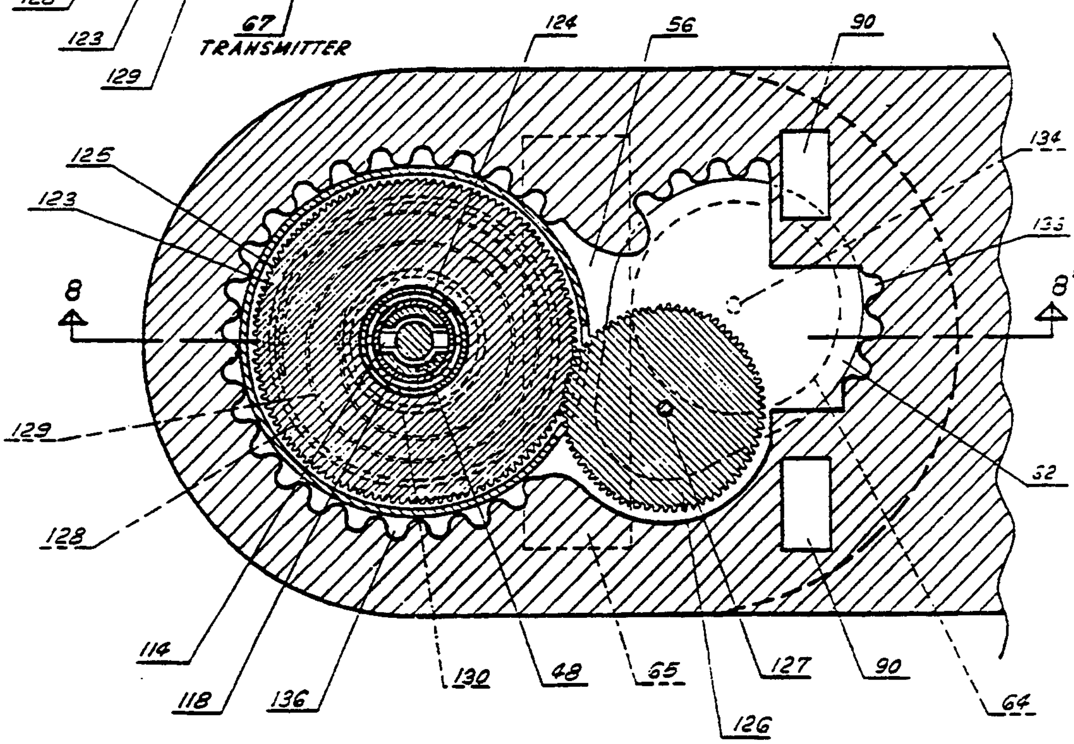

FIG. 9

Advancing the State of the Art

- efficient, reliable, adaptable
- minimum perceived effort
- variable frequency and duty cycle
- diverse load requirements
- adverse environmental conditions

- targeted material selection
- design optimization through computer aided engineering
- microprocessor-based power management
- novel packaging and miniaturization technology
- compatiblize electronic and ergonomic constraints

A challenging synthesis of technologies and organizations against the backdrop of a microelectronics revolution

"OVERVIEW OF DEVELOPMENTS IN SOUTH AFRICA"

(UNAVAILABLE)

Mr. Etienne Rijkheer

SYZYGY
Capetown, South Africa

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